REVIEW

IMPLICATIONS OF TEPHRA (VOLCANIC ASH) FALL-OUT ON THE OPERATIONAL SAFETY OF THE SENDAI NUCLEAR POWER PLANTS

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A DIFFICULTY ENCOUNTERED IN PREPARING THIS REVIEW HAS BEEN ACCESS TO DOCUMENTS AND DATA THAT ARE ONLY PUBLICLY ACCESSIBLE IN JAPANESE LANGUAGE VERSIONS. THIS MAINLY APPLIES TO DOCUMENTS, GUIDES AND SUBMISSIONS FROM THE NUCLEAR REGULATORY AUTHORITY (NRA) - THAT SAID, IT IS UNDERSTANDABLE THAT THE NRA IN PRESSING AHEAD WITH INTRODUCTION OF THE *NEW REGULATORY REQUIREMENTS* QUITE CORRECTLY PRIORITISED JAPANESE LANGUAGE VERSIONS. HOWEVER, THIS MAY HAVE GIVEN RISE TO TWO AREAS OF INCOMPLETENESS IN THE REVIEW: FIRST, THAT THE LITERATURE SURVEY MAY NOT HAVE BEEN COMPLETELY COMPREHENSIVE AND, SECOND, THE SHORT TIME AND LIMITED RESOURCES AVAILABLE FOR TRANSLATION HAVE NOT BEEN ENTIRELY SUFFICIENT TO TRAWL THROUGH THE JAPANESE LANGUAGE VERSIONS ACTUALLY IDENTIFIED AND ACCESSIBLE.

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EXECUTIVE SUMMARY

The Review comprises three aspects of the present nuclear safety measures relating to the functioning of the Sendai nuclear power plant (NPP) when subject to high levels of tephra ash fallout from an erupting volcanic event – the Review does not consider in any great depth other volcanic hazards, such as pyroclastic density flow, etc., nor how these hazards might act in combination with tephra fall to challenge the resilience of an operational NPP.

First, the Review seeks to describe the present regulatory constraints and requirements placed upon the Sendai NPP operator to adequately forecast the nature and risk of occurrence of the general volcanic hazard; second, the effectiveness of the screening process adopted to determine which volcanoes and to what extent these represent a hazard to the Sendai NPP; and, third, if the severity of the projected volcanic event complies with the 2013 revised *design-basis* requirements of the Nuclear Regulation Authority (NRA) and, in this regard, if the preparation and countermeasures at the Sendai NPP site are sufficient to protect the region from a significant radiological outcome in the event that nuclear plants are subject to a prolonged period of tephra fallout.

First inaugurated in 2012, the NRA issued draft guidelines in early 2013 for the assessment of, amongst other extreme natural phenomena, the risks and hazards of volcanic activity. The draft *New Safety Standards* for *Volcanic Assessment* adhered to the template of the recommendations of the International Atomic Energy Agency (IAEA), particularly in the adoption of a methodological evaluation process and, importantly, that the process overall was to determine and put in place the parameters of volcanic hazard-specific *design-bases* custom developed for each, specific nuclear power plant site.

However, the final *Assessment Guide of Volcanic Effects to the Nuclear Power Plan*, first issued as a draft revision in June 2013, lacks sufficient discipline and enforcement to ensure that operators, like Kyushu Electric at Sendai, rigidly adhere to sufficiently comprehensive risk and hazard evaluation procedures. For example, at the Sendai NPP the worse case tephra fall is not drawn from a probabilistically determined range of possibilities but it seems, and very much contrary to the recommended IAEA approach, from a single geologic event reckoned to have occurred some 12,800 years ago. Relying upon a single past event from the surviving geologic record, particularly if there is no surviving contemporaneous human account, is likely to be accompanied by uncertainty, particularly in that the gauge of potential, future volcanic activity could be underplayed if smaller, past volcanic events have been masked and missed from the geologic record, and/or if the physical record of a tephra fall event had been eroded or diffused over time

There are similar shortfalls in Kyushu Electric's promotion of the Volcano Explosivity Index (VEI) to screen out certain capable volcanoes, particularly in the assertion that more frequent VEI 3 to 6 magnitude events will have no adverse affect on the Sendai NPP, and that it is only the continental-scale VEI 7 event that would challenge the existing *defence-in-depth* resilience at Sendai. Essentially, VEI is a somewhat empirical measure of past and observed volcanic eruptions, taking into account the volume of the ejecta, plume cloud height and a number of qualitative observations, but it is not generally considered to be a portend of future eruption frequency nor, indeed, a yardstick of eruption magnitude nor of any particular effect (such a tephra fall).

Generally and, perhaps, more directly relating to the highly energetic volcanic hazards such a pyroclastic density flows and surges, is the over-reliance upon a single episode of relatively recent academic work that formulates a model whereby it is claimed possible to predict a forthcoming eruption – even if this monitoring methodology is reliable, the tolerance of the timescales available could be either too long (~tens to hundreds of years) to provoke action, or too short (weeks and months) in that there would be insufficient time to prepare and transfer the 400 to 1,000^{+}tonnes or so of intensely radioactive fuel off the NPP site for safe and secure storage elsewhere in Japan.

However, this Review, confined to tephra fall, does not explore the very challenging, if not impossible, logistics of transferring such a large amount of intensely radioactive spent and short-cooled nuclear fuel.

The Review assesses the adequacy of the measures in place at Sendai NPP to cope with a prolonged tephra fall. Kyushu Electric assumes a maximum tephra deposited layer of 12 to 15cm depth which, in terms of superimposed wet ash loading on the various flat roofs and tanks dispersed around the NPP site, is within the roof design loadbearing limits – to manage this ash layer Kyushu Electric reckon that 30, two-man crews would clear the ash in 14 or so days. The Review considers this somewhat optimistic since, adopting UK physical labour rates for shifting water sodden, 'sticky' tephra would occupy around 30 days – if the tephra fall continued whilst the tephra layer was being cleared – a possibility not considered by Kyushu Electric - to keep abreast of a relatively moderate tephra fall rate of 1.3cm/hr about 40 or so two-man teams would be required to cover three-shift working.

On the basis of the 12,800 year geologic record of ash fall adopted by Kyushu Electric as the worse case, if by chance there occurred a change of wind direction from the north to an easterly, the geologic record of ash fall layer thickness in the vicinity of Sendai NPP increases to about 30cm that, if wet and accumulating uncleared, would exceed the roof superimposed limits by x1.18 and x1.4 of the spent fuel buildings serving reactors R1 and R2 respectively, thereby introducing the risk of roof damage and possible collapse over one or both of the spent fuel storage ponds.

It is generally acknowledged that as a result of prolonged tephra fall, the local electrical distribution grid and, particularly, exposed substation switchgear and transforming equipment, would be at risk of flashover and failure. Kyushu Electric assume that this would result in a loss of offsite power (LOOP) for 7 days during which Sendai NPP would be dependent upon the on-site emergency diesel generators and perhaps mobile-mounted generators if, that is, these could be brought onto the site via difficult to pass roads during the tephra fall. One aspect of maintaining diesel generator supplies is the need to change the engine aspiration and generator plant room filters to protect the mechanical sliding and rotating parts against seizure – for example, the US Columbia NPP tephra fall countermeasures include for a generator filter change completed every 2.3 hours of runtime and, similarly, for the plant room filters every 3.6 hours runtime. In comparison, the countermeasures detailed for the Sendai NPP do not include for any filter changes to the emergency diesel enclosure ventilation system, although the generator engine aspiration filters are reckoned, according to Kyushu Electric, to require replacement every 26.5 hours runtime (compared to 2.3 hours for Columbia) with the filter change operation occupying 8 personnel for about 2 hours. The Review expresses a number of reservations about the practicable applicability and source data deployed in the Kyushu Electric analysis.

Interestingly, the Kyushu Electric plans and countermeasures do not extent that much into the public sector areas away from the NPP site. Of course, tephra fall and deposition is likely to be widespread making road vehicle movement difficult, if not impassable, and with continuing tephra fall natural light could be very limited and, at night, if the local electricity power distribution system has failed, illumination of thoroughfares and buildings will be dependent upon stand-alone generator supplies. Moreover, buoyant, vesiculated pumice might be swept down the River Sendai, accumulating downstream to give rise to localized or, indeed, widespread flooding, all exacerbated by tephra blockage of drains and culverts. Also, there might be a high call on emergency services personnel to respond to other volcanic effects that might be more intense nearer the active volcanic vent(s).

In other words, in times of high volcanic activity, and for not readily defined periods thereafter, Sendai NPP might find itself competing for human and equipment resources that are equally or if not more so in demand elsewhere. It may be necessary for Sendia NPP personnel to venture out well beyond the NPP boundaries to maintain essential routes of manpower, equipment and fuel to the site, all of which could stretch the human resources necessary to maintain a stable and nuclear safe situation within the NPP site. Similarly, human resources contracted to attend the NPP site, both permanently employed and contracted labour, etc., may under conditions of duress prioritise their loyalties to family, to protect their homes and/or to evacuate to other less volcano affected areas of Kyushu or, indeed, elsewhere to greater Japan.

It is conceivable that in certain circumstances, Sendai NPP might find itself stranded and under-resourced, tipping into an intolerable and increasingly unstable situation. There is very little to indicate in both the summarised Kyushu Electric and NRA assessments that this possibility has been recognized and prepared for. More so, the relatively small-scale exercises and rehearsals undertaken at Sendai to demonstrate Kyushu Electric's readiness and pre-planned countermeasures to manage tephra fall (involving the removal of a hundred or so meters of simulated tephra layer from a hardstanding surface on a clear, dry day) may not be at all representative of a real volcanic event in the region of Kyushu Island.

In summary: Although it has to be acknowledged that NRA's introduction of the 2013 *Volcanic Assessment Guide* is a significant step forward from the pre-Fukushima Daiichi era when no regulatory volcano evaluation procedures were in place, this first version of the *Guide* is a poor reflection on the methodological approach recommended by the IAEA. Moreover, the *Guide* does not instill sufficient discipline on the licensee to ensure that the volcanic hazards assessment is both comprehensive and meaningful, nor does it mandate the licensee to explore and establish NPP-specific *design-bases*, so much so that, instead, the outcome of the site assessment exercise is more akin to tinkering around the edges than that of addressing the fundamental resilience and *defence-in-depth* of the NPP and its site.

There is another weakness in the *Guide*, this being that it directs the operator to evaluate the affects of each volcanic effect separately in a mechanistic manner. However, the tephra fall subject of this Review is likely to have widespread and concurrent affects on a diverse range of activities and functions both on and off the NPP site – it is a *common-mode* initiator: it may cause machinery to seize; roofs may be damaged or collapse by ash overloading; off and on site electricity equipment may short-circuit and trip; transport routes to and from the NPP site may be impassable; NPP staff may be unable, or unwilling, to attend the site during the uncertainty of a volcanic eruption; and so on. Any one affect of ash fall may not, in itself and alone, be sufficient to bring the plant down, but when acting in combination and possibly chaotically, the plant's overall resilience may fail. Similarly, the affects of ash fall should also be considered in combination with the affects of other volcanic hazards, such as pyroclastic flow and surges.

This is the fundamental limitation of the NRA-Kyushu Electric approach, essentially being that it defines and addresses individual aspects of plant performance and resilience without considering the outcome of the whole.

The Kyushu Electric submission to the NRA, as summarized by the NRA, reveals that this first attempt by the new nuclear safety regulator to introduce a systemised and comprehensive volcanic effect NPP site evaluation may not have been entirely successful.

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PART I – THE LEGAL AND REGULATORY FRAMEWORKS

DESIGN-BASIS HAZARD ASSESSMENT OF NPPS – PRE-FUKUSHIMA DAIICHI

Prior to the catastrophic events at Fukushima Daiichi of March 2011, the nuclear safety regulation applying to Japanese nuclear power plants (NPPs) comprised a hierarchal framework of state laws and ordinances, with these being put into practice by a series of regulatory guides.

As prescribed by the *Atomic Energy Basic Act*, Ministerial *Orders* and *Ordinances* are attached to or associated with the *Reactor Regulation Act* and the *Electricity Business Act*, being the two main laws for nuclear safety applied to NPPs via the *Regulatory Guides*. Individual and issue/topic-specific *Regulatory Guides* were then, prior to September 2012, derived and applied by a statutory agency, *Nuclear Safety Commission* (NSC), functioning in parallel to the *Nuclear and Industry Safety Agency* (NISA), and the *Ministry of Economy, Trade and Industry* (METI).

NSC Regulatory Guides (NSCRGs) for the NPPs were grouped into four classes, each relating to a specific application (power generating reactors – L, research reactors – D, fuel cycle facilities – F, and general guidance, such as decommissioning, emergency planning, etc – T) with, for example all of the NSCRGs dealing with NPPs being prefixed with 'L', such as NSCRG:L-DS-I.0.

The power generating class L is segregated into five divisions (siting - ST, design - DS, safety evaluation - SE, radiation exposure – RE, and accident management - AM) with the individual guides expressed at two levels (*Level I* and *Level II*) within each division, with the exception of accident management for which all NSCRGs were Level II.[footnote 1] Examples of the NSC Level I Regulatory Guides are NSCRG:L-ST-I.0 *Reviewing Nuclear Reactor Site Evaluation and Application Criteria* and NSCRG:L-DS-I.0 *Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities.*[2]

Both NISA and NSC used the NSCRGs as a basis for the nuclear safety reviews, although these are not *'requirements'*, nor are they legally binding. However, since the national laws (the *Acts* and ministerial *Orders* and *Ordinances*) do not specify and lay down standards of nuclear safety, the assumption seems to have been that the NSCRGs, viewed as a whole, stipulated the minimal *'design-basis'* requirement. In this respect, the stated purpose of NPP design guideline NSCRG:L-DS-I.0 is to establish *"the basis of the judgment for adequacy of the design [is] to ensure safety at the Safety Review. . ."* at which point a construction permit is approved so, it follows, at this stage the proposed NPP design meets the requirements of L-DS-I.0.

In these terms, meeting the requirements of the NSCRG L-DS-I.0 '*ensures*' adequate design safety and, hence, establishes the *design-basis* of the NPP. In nuclear jargon the *design-basis* is the range of conditions and events taken explicitly into account in the design of the NPP,

1 Each division of the NSCRGs is headed by a general guide, such as NSCRG:L-DS-I.0 appended to which are a series of more detailed and/or topic specific guides such as NSCRG:L-DS-I.02 *Reviewing Seismic Design of NPPs* and, then, in greater application Level II guides such as NSCRG:LDS-II.05 *Geological and Ground Safety Examination of NPPs.*

2 A listing of the NSCRGs is at http://www.nsr.go.jp/archive/nsc/NSCenglish/guides/nsc_rg_lwr.htm

according to established criteria, such that the facility can withstand them without exceeding authorised conditions and limits by the planned intervention operation of safety systems and/or passive barriers. Put another way, the *design-basis* is a set of conditions and/or circumstances that the NPP will withstand without yielding an intolerable outcome – there might co-exist several so specified *design-basis* circumstances, each representative of a particular accident, an external natural phenomena, and so on.

By definition the *design-basis* is not necessarily the worst-case accident or circumstances that could beset a NPP – worst case scenarios might be screened out on grounds of acceptably remote frequency of occurrence (ie probability), etc..

SHORTCOMINGS OF THE REGULATORY FRAMEWORK EXPOSED BY FUKUSHIMA DAIICHI

The Fukushima Daiichi catastrophe revealed fundamental flaws in the Japanese approach to hazard analysis, particularly in the area where it considered itself to excel, that is in defining and accounting for uncertainties in the probabilistic seismic hazard analysis (PSHA). These shortcomings related to epistemic uncertainties arising from incomplete knowledge of seismic processes and ranges of severities and, unfolding from the intrinsic randomness of seismic events, uncertainties that give rise to aleatory variability.[Reference][1] In seismic hazard analysis, the distinction is that epistemic uncertainty might be reduced by gathering more data and/or by refining the forecasting technique whereas, the contrary, the aleatory uncertainty derives from the randomness of inputs that cannot be forecast in detail nor reduced through further research at the time.[3]

The combination of the *Great East Japan Earthquake* and its tsunami that struck the eastern seaboard in March 2011 revealed the depth and complexity of both epistemic and aleatory uncertainties extant at that time.

Fukushima Daiichi demonstrated that although probabilistic tsunami hazard analysis (PTHA) is derived from PSHA it incorporates quite different uncertainties: it has to account for far-field sources, as well as very local circumstances such as the shelving rate[4] and local state of the tide. Applied to the site of NPP, other factors quite possibly not even considered at the time of the design, add to the complexity of the overall probabilistic hazard analysis which for Fukushima Daiichi, should have taken account of the terracing and enclosing steep earthwork bunds of the site;[5] the labyrinth of service rooms and ducts and linking the nuclear islands below normal sea level became inundated and inaccessible; and the location and defences of the emergency generators whose failure, along with the loss of offsite power (LOOP) resulted in the disastrous station blackout (SBO) that inexorably led to loss of the reactor(s) fuel core cooling and, with this, the ensuing the radiological catastrophe.

Post-tsunami events at Fukushima Daiichi demonstrated the necessity to maintain both reactor core and spent fuel pond cooling over a wide range of events, because this is the

3 Of course separating aleatory variability and epistemic uncertainty concerns the limits of what could be learned in the future. In effect, there is no aleatory variability in the earthquake process because, in principle, earthquakes are responding to stresses and strains in the earth so that, given enough time, sufficient data and understanding will become available to develop reliable and detailed models of the earthquake process. In other words, since the earthquake process is in theory knowable, there is only epistemic uncertainty due to our lack of knowledge that will be reduced in time.

4 The shelving rate (ie the shallowing of seawater depth in the approach to the coastal beach) determines the run-up height of the tsunami wave train.

5 The earthwork bunds enclosing the southern section of the Fukushima Daiichi acted to reflect back and thereby heighten the tsunami inundation amplitude over the site area.

most effective method of preventing significant radioactive releases. The accident has indicated that the events now needing to be protected against include large fires and explosions, extreme natural phenomena including hazards from local and regional volcanic activity, station blackouts of indefinite duration, and combinations of internal failures that can cause the loss of normal and backup core cooling that provide protection from the traditional design-basis events.[2]

The pre-Fukushima Daiichi version of NSCRG:L-DS-I.0 dealt with natural phenomena as follows:

> *". . .* ***Guideline 2. Design Considerations against Natural Phenomena***
>
> *(1) SSCs[6] with safety functions shall be assigned to appropriate seismic categories, with the importance of their safety functions and possible safety impacts of earthquake-induced functional loss taken into consideration, and be designed to sufficiently withstand appropriate design seismic forces.*
>
> *(2) SSCs with safety functions shall be so designed that the safety of the nuclear reactor facilities will not be impaired by other postulated natural phenomena than earthquake. SSCs with safety functions of especially high importance shall be of the design that reflects appropriate safety considerations against the severest conditions of anticipated natural phenomena or appropriate combinations of natural forces and accident-induced loads. . . ."*
>
> my *highlighting*

In this way, until Fukushima Daiichi, the primary concern with respect to natural hazards was firmly rooted in seismic events, with assessment of all other natural phenomena, including volcanic activity, being left largely to the discretion of the operator/licensee.

The Japanese Government (Diet) *Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company*[3] reported in July 2012 recommending immediate root-and-branch changes to the laws and regulations governing nuclear power and its safety, including that:

> *". . . Once such new systems, laws and regulations are established, they must then be retroactively [retrospectively] applied to existing reactors. It should be explicitly stated in the laws that reactors that do not meet the new standards should be decommissioned or otherwise dealt with appropriately. . . "*
>
> my *emphasis* and *[added explanation]*

POST-FUKUSHIMA DAIICHI AND THE TRANSITION TO A NEW DESIGN-BASIS

Inaugurated in September 2012, the Japanese *Nuclear Regulation Authority* (NRA)[7] in February 2013 issued the *Draft New Safety Standards for NPPs*[4] acknowledging certain vulnerabilities and failures in the existing NPPs, including an absence of effective severe accident management measures. The outline draft (Part I) considered means to improve the *Design-Basis Safety Standards* as follows:

6 SSCs - Structures, Systems, and Components

7 The NRA was created by separating the functions of the former *Nuclear and Industrial Safety Agency* (NISA) industry watchdog from the pro-nuclear Ministry of Economy, Trade and Industry (METI).

"... • *Safety measures against natural phenomena (e.g., tornados, forest fires) and external man-made hazards (e.g., an aircraft crash), the reliability of off-site power supply, ultimate heat sink and the functions of SSCs, as well as fire protection measures on site should be strengthened ...*"

In the following April, 2013 a further outline of the *New Regulatory Requirements* (NRRs) – *Design Basis*[5] added more substance to defining the natural phenomena being included within the design-basis under *Guideline 2*, for example:

"... *2. General Technical Requirements for Nuclear Reactor Facilities*

(1) Design Considerations against Natural Phenomena

...

(Natural phenomena other than earthquakes)

... the safety of the NPP nuclear reactor facilities will not be impaired and be of design that reflects appropriate safety considerations against the severest conditions of anticipated natural phenomena ..."

[p9 of 5] my truncation ...

The natural phenomena referred to in the NRRs are clarified to be:

"... *D. "Anticipated natural phenomena" refer to on-site natural phenomena possible to occur including flood, wind (typhoon), tornado, freezing, rainfalls, snowing, lightning, landslide, volcanic effects, biological effects, forest fires, etc*

E. "The severest conditions" refer to the conditions assumed to be the severest according to the latest scientific and technological knowledge concerning the natural phenomena under consideration ..."

[p10 of 5] my *emphasis*

The next step in the review of the draft NRRs was the development of a series of draft guides,[6][8] such as, of interest here, *'The Assessment Guide of Volcanic Effects to the Nuclear Power Plant'*, issued as a draft revision in June 2013,[7] this and other NRRs being put in force on 8 July 2013 under the general title the *New NRA Regulations*. This specific hazard *Assessment Guide*[9] is the NRA's practicable implementation of the Diet Investigation Commission's[3] final report recommendation that:

"... *Nuclear operators should conduct comprehensive risk analysis encompassing the characteristics of the natural environment. In the analysis, they should include the external events, not only earthquakes and their accompanying events but also other events such as flooding, volcanic activities or fires, even if their probabilities of occurrence are not high, as well as the internal events having been considered in the existing analysis. Nuclear regulators should check the operators' analysis ...*"

my *emphasis*

So, by July 2013 in force were *New Regulatory Requirements* (NRRs)[8][10] obliging the

8 Some, if not all of the Draft Guides were put out to public consultation and, it is believed, at this stage the *Japan Nuclear Energy Safety Organisation* (JNES) may have contributed to revision and amendment – certainly this was the case for the seismic ground motions, but JNES does not seem to have contributed directly to the Assessment Guide of Volcanic Effects of APPENDIX I.

9 No such volcanic hazard specific guide existed prior the regulatory changes brought about by the accident at Fukushima Daiichi, as noted by the Diet Investigation Commission comprehensive risk assessments addressing earthquake, tsunami, fire, volcano, collapse of slope had not been conducted.

10 *Act for the Establishment of the Nuclear Regulation Authority* (No 47, June, 2012) and under the terms of Article 17 of the *Supplementary Provisions of the Act for Establishment of the Nuclear Regulation Authority*. The revised Act introduced a new regulation system based on the lessons learned from the Fukushima Daiichi accident, the latest technological findings, trends in overseas regulations including regulatory requirement stipulated by the IAEA and other international organizations, as well as other factors.

operators of NPPs to give account to extreme and/or rare natural phenomena, including circumstances hitherto considered to be incredible and therefore discounted in the nuclear safety case - amongst these the operator is now required to compile and assessment of volcanic activity.[11]

This Review considers just one of the volcanic hazards identified in the *Volcanic Assessment Guide*, the impact of tephra ash fall, and how this particular effect could impact upon the nuclear safety operations of the Sendai NPPs that are presently undergoing the final NRA approval procedures for recriticality and resumption of electricity generation.

11 APPENDIX I includes an unofficial translation of the Contents Listing of *'The Assessment Guide of Volcanic Effects to the Nuclear Power Plant (Draft)'* - APPENDIX II provides the (English) tentative titles of new and/or strengthened NRA Safety Guides.

PART II – VOLCANIC HAZARDS

THE VOLCANIC HAZARD

Volcanic events rarely produce just a single effect. Eruptions usually initiate complex sequences of processes that trigger and yield a wide range of volcanic phenomena that might be summarized to include the following (see FIGURE 1):

Eruption Columns and Clouds: An *explosive eruption* comprises solid and molten rock fragments or *tephra* and volcanic gases ejected into the atmosphere. The largest rock fragments or *bombs* usually fall back to the ground within 3 to 4 kilometers of the *vent*. Small fragments and temporarily self-buoyant particles of volcanic glass, minerals, and rock make up the volcanic *ash* dispersing as a billowing *eruption column*. Eruption columns can grow rapidly, reaching more than 20km altitude in less than 30 minutes, forming an *eruption cloud*. Large eruption clouds can extend hundreds of miles downwind, resulting in fallout or *ash fall* deposition over enormous land and ocean areas.

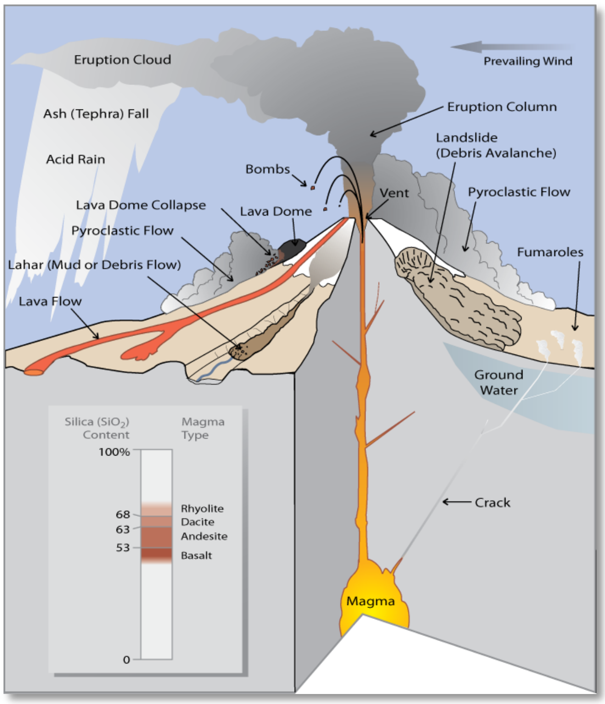

FIGURE 1 PRINCIPLE VOLCANIC ACTIVITIES FOR A STRATOVOLCANO SOURCE

Pyroclastic Falls: Pyroclastic-fall deposits may consist of *pumice*, *scoria*, dense *lithic* material, crystals, or any combinations of these, and range in size from ash particles and slithers (diameter less than 2 mm) through to *lapilli* (2 to 64 mm), and to *blocks* and *bombs* (more than 64 mm).

The superimposed weight of deposited pyroclastic falls, often referred to as *tephra fall*, may cause failure and the collapse of roofs of buildings. When on the ground as a layer of a few centimeters ash is sufficient to impede and halt rail, road and air traffic with for the latter, prohibitions restricting flying through and near to ash clouds. Tephra intake can result in seizure of machinery such as pumps and engines because of inclusion of highly abrasive silica, and the fine ash particles may block air and water filters.

Damp or wet pyroclastic-fall deposits are much heavier: First, a fall deposit of dry ash and lapilli 10cm thick may weigh 20-100 kg/m, whereas a wet layer of the same thickness may weigh 50-150 kg/m this increase being significant when added to the roof of a building. Second, wet ash is much more cohesive than dry ash and may adhere to electric power and telephone lines and to roofs of buildings, and will interfere with movement on foot or by wheeled vehicles. The low permeability of tephra is likely to accelerate surface water run-off, result in drain blockage and localised flooding.

> **EXAMPLE: The tephra fall of about 1km^3 DER from the 1980 eruption of Mount St. Helens (USA) gave rise to a secondary maximum of uncompacted tephra thickness increasing from about 1.5 to 5cm at about 300 km from the volcano. The aggregation of very fine ash into larger particles caused premature fallout at the secondary thickness particles during the Mount Mazama (Oregon, USA) around 5,700 BC where the compacted teprha fallout compacted thickness increased from about 17 to 40cm at a distance of about 150 to 250km from the vent source.**

endnote reference [9][10]

Volcanic Gases: During eruptions and also when in apparent *repose*, fissures in the local geological strata allow pressurised gases to reach the surface through relatively small openings called *fumaroles*. About 90% or more of all gas emitted by volcanoes is water vapour (steam), most of which arises from heated *groundwaters*. Other gaseous components include carbon-dioxide, sulphur-dioxide, hydrogen sulfide, hydrogen, and fluorine.[12] The sulphur-dioxide is available to react with water droplets in the atmosphere to create weak concentrations of sulphuric acid as a corrosive aerosol mist or *acid rain.*

Vulcanian[13] Blasts - Explosions, Vertically or at some Lower Angle: Vertically directed explosions may produce mixtures of rock debris and gases that flow, motivated chiefly by gravity, down one or more sides of a volcano. A volcanic explosion that has a significant low-angle component is referred to as a *lateral blast*. Such a blast may produce a mixture of rock debris and gases hundreds of meters thick traversing at high speed along the ground surface as a *pyroclastic flow*, a *pyroclastic surge*, or both. The high velocity of the mixture of rock debris and gases, which may be at least 100m/s, is due both to the initial energy of the explosion and to gravity as the mixture moves downslope.

> **EXAMPLE: A lateral blast at Mount St. Helens (USA) in 1980 moved outward at a speed of at least 100m/s, devastated an area of 600 km^2 out to a distance of 28km from the volcano, and killed more than 60 people. A similar blast in 1956 at Bezymianny volcano (USSR), affected an area of about 500km^2 out to a distance of 30km from the volcano. Both of these events were closely associated with debris avalanches. Air shock waves can, apparently, couple to the ground sufficiently to casue damage to buildings at 100km distance.**

[11][12][13]

Lava Flows and Domes: Molten rock *magma* that pours or oozes onto the Earth's surface and forms *lava flows* and/or *lahars*. The gravity driven dispersion of lava flow is determined by the viscosity and temperature, so that a magma source rich in *silica* (silicon-dioxide) is viscous and thwarted, whereas low-silica *basalt* lava can form fast-moving (20 to 50km/hr) streams or can spread out in broad, thin sheets as much as several kilometers wide. Lava flows of higher-silica *andesite* and *dacite* sourced magma tend to be thick and sluggish, being

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12 Generally the airborne levels of vented gases at any reasonable distance (10s of km) from the vent are too low as to have any immediate serious toxic outcome – for example, magma degassing from Mount St Baker yielded 75ppb and 2ppm for H_2S and CO_2 respectively, that is well below levels at which there would be any great health concern – see McGee K A, et al, *'Quiescent Hydrogen Sulfide and Carbon Dioxide Degassing from Mount Baker, Washington'*, Geophysical Research Papers, V28 No 23 2001 – that said, there are a number of epidemiological studies describing the broader health issues – see Hansell A, Oppenheimer C, *'Health Hazards from Volcanic Gases: A Systematic Literature Review'*, Arch Environ Health, December 2004

13 Vulcanian Eruption – a short, explosive or blast-like eruption lasting a few seconds or minutes.

arrested relatively short distances from the vent. *Dacite* and *rhyolite* lavas are extremely sluggish and form irregular mounds called *lava domes* around the vent location.

Pyroclastic Flows: In effect, *pyroclastic flows* are high-density, high-speed avalanches of hot ash, rock fragments, and gas generated during explosive eruptions or when the steep side of a growing *lava dome* collapses and structurally disintegrates. The magma, debris and gaseous mass of a pyroclastic flow can maintain high temperature, at about 800°C and move across the local and regional terrains at speeds of 150 to 550km/hr. Pyroclastic activity can be maintained at considerable distances from the source volcano and fan out and disperse over wide areas.

EXAMPLE: About 6,850 years ago, some pumiceous pyroclastic flows erupted during the climactic eruptions of Mount Mazama (Oregon, USA) moving 231m upslope to cross a divide 17km from the volcano and ultimately reached down a valley a distance of 60km from the vent.

[14]

Pyroclastic Surges: Pyroclastic surges are turbulent, low-density clouds of rock debris and air or other gases, perhaps accompanied by steam, that move over the ground surface at high speeds. Both hot and cold pyroclastic surges damage or destroy structures and vegetation by impact of rock fragments moving at high speeds and may bury the ground surface with a layer of ash and coarser debris tens of centimeters or more thick .

EXAMPLE: During the 1902 eruption of Mount Pelee on Martinique, a surge cloud of hot ash and gases swept into the town of St. Pierre at an estimated speed of 160 km/hr or more - about 30,000 people died within minutes, most from inhalation of hot ash and gases

[15]

Volcano Landslides: A *landslide* or *debris avalanche* or *lahar* is a rapid downhill movement of sub-terrain rocky, surface overburden and other materials (snow, ice, vegetation, etc). Volcano landslides range in size from small movements of loose debris on the surface of a volcano to massive collapses of the entire summit *caldera* and/or *flank* of a volcano. *Strato-* or steep-sided volcanoes are susceptible to landslides because they are built up partly of successive layers of loose volcanic rock fragments, loosely bound together with clay overburden accumulated during periods of repose. Landslides at coastal volcanoes may involve the sudden dislodgement of many thousands of tonnes of debris and magma plunging into the sea, generating the seeds of a train of tsunami – about 5% of all tsunamis stem from volcano collapse and/or interaction of the hot magma with seawater.[16]

EXAMPLE: A debris avalanche that occurred at Mount Shasta (California USA) between about 300,000 and 360,000 years ago travelled more than 64 km from the summit of the volcano, covered more than 675 km^2 , and had a tephra volume of at least 45 km^3.

[17]

FREQUENCY AND PREDICTABILITY OF ERUPTION

There is, unfortunately, no certain method of distinguishing long dormant volcanoes that are capable or eruption from apparently extinct volcanoes.[18]

This is because volcanoes often undergo long periods of repose between episodes of volcanic activity, although some observers deduce a pattern in Holocene volcanoes of mean repose intervals of ~0.45ka prior to moderately explosive activity, and that the mean repose interval increases to ~1.5ka before the most explosive eruptions.[19] Moreover, volcanoes can remain dormant for thousands and tens of thousands of years between bouts of eruptive activity.

Of interest here is the coalescence of probabilities between the hazard, the volcanic eruption, and the relative location of the NPP site. Usually, this can be broken down into three distinctive probabilities: the probability that the eruption will occur within the lifetime on the NPP (a lifetime that may extent to include a decommissioning period); the probability that an eruption will occur within a specific geographical area; and the probability that one or more volcanic hazards will affect the NPP site, given that an eruption occurs.

The complexity of the processes steering these compounding probabilities renders forecasting an actual event somewhat uncertain and highly susceptible to unreliability.

Even with due allowance for evolutionary changes in behaviour of the magma in the underlying reservoir, a volcano is most apt to do in future much the same as it has done in the past - this axiomatic concept seems to offer the most valid approach to an assessment of volcanic hazards and risks at any NPP site.

CATEGORISING VOLCANIC RISK AND HAZARD

As previously noted, a volcano is most apt to do in future much the same as it has done in the past. On this basis the past record of volcanic activity is reckoned to be a reliable portend and this, in various interpretations, forms the basis of the risk assessment of volcano behaviour. For example:

Volcanic Explosivity Index: The *Volcanic Explosivity Index* (VEI) somewhat empirically provides a basis for comparison of eruptions by taking into account the volume of the ejecta, plume cloud height and a number of qualitative observations – the VEI scale is open-ended, presently limited to 0 to 8, where 8 represents an eruption ejecting 1,000 km^3 of tephra to a cloud-plume height in excess of 25 to 50km.[14]

VEI is not generally presented as a specification yardstick when assessing the suitability of NPP sites (both the proposed sites and, retrospectively when assessing existing NPP sites

14 The VEI scale is logarithmic, that is with each interval above VEI 2 being logarithmic, with each interval being a tenfold increase in the ejecta mass criterion. Weaknesses of the VEI scale projection include that all ejected material are treated alike, so the influence of larger fragments (of more or to a lesser extent) are not taken into account in the distal tephra ash fallout and, importantly if VEI is adopted as a probability or threshold value for hazard and risk analysis, since it does not directly take into account the power of the eruption and includes qualitative observations, it is difficult to compare with historic and/or unobserved past eruptions.

such a Sendai). For example, the *International Atomic Energy Agency* (IAEA) site selection guide (see later) only defines but does not explicitly recommend the use of VEI for NPP site assessment studies although, that said, VEI assessments of past (witnessed) volcanic events provide a useful comparative measure, suggesting that a VEI range of 3 to 6 events is of practical interest in relation to NPP sites.

TABLE 1 EXAMPLE OF VOLCANO EXPLOSIVITY INDEX – VEI [20]

VEI	EJECTA VOLUME km³	PLUME HEIGHT km	GLOBAL FREQUENCY a^{-1}	SCALE OF EFFECTS OF EXAMPLE ERUPTIONS
1	<0.001	0-1	>10^3	Very localised effects – channelled pyroclastic and debris flows - affected areas <10km from volcano vent – examples Mount Unzen, Japan 1990-1993.
2	0.001-0.01	1-5	50	Typically isolated explosive, short-lived eruptions - channelled pyroclastic and debris flows - affected areas <10km from volcano vent –example Mount Stromboli, Sicily 1985
3	0.01-0.1	3-15	1	Wide variation of effects sometimes extending > 50km – example Miyake-Jima, Honshū 1983.
4	0.1-1	10-25	0.1	Wide variation of effects, long-lived with substantial effects <10km with channelled flows exctending >50km sometimes extending > 50km – example Tolbachik, East Russia 1975.
5	1-10	>25	0.02	Often substantial effects <10km, volcano structure may be devastated, channelled flows to <100km – examples Mount St Helens, USA 1980 – Fuju 1707.
6	10-100	>25	0.01	Areas devastated <30km, substantial effects <100km, channelled flows >100km – example Krakatau + tsunami, 1883.
7	100-1000	>25	0.001	Regions devastated 100km or more, worldwide there have occurred four known Holocene VEI 7 eruptions – example, possibly Taal, Luzon Island, Philippines, 1815.
8	>1,000	>25	<0.0001	No Holocene eruptions of VEI 8 and greater – this scale of eruption has continent-scale effects – example Yellowstone, US, 600ka.

By deterministic means it is quite practicable to relate an estimate of the potential tephra fall and deposited layer thickness to the VEI providing, that is, reliable projections of the location of the erupting vent, the column height, total erupted mass and the tephra grain size distribution are available. This approach has been collected together and applied to the built but never fuelled and commissioned Bataan NPP located on the Luzon Peninsula, Philippines.[21][15,16]

15 The Bataan PWR NPP was constructed in late 1970s and early 1980s but never commissioned into service. The project, financed and built by US interest was controversial because, for one thing, it challenged whether the hazards assessments for the siting were apparently the responsibility of United States NRC, although the NRC ultimately deemed at had no legal role in reviewing the hazard assessments. The controversy over the siting arose because of the close proximity (15km) of the Bataan NPP to the potential active Mount Natib volcano and doubts about the US consultancy EBASCO's 1977 volcanic hazard assessments. Not at all anticipated, was the violent eruptions of Mount Pinatubo in 1991, located approximately 60km north of the NPP, and which deposited a tephra layer of ~6cm thickness over the defunct NPP site.

16 The Bataan NPP example illustrates the advances in forecasting volcanic events. On that basis that the repose period preceding VEI 6-7 events follows a log-logistic probability distribution, as postulated in 2006,[19] the probability of a Mount Natib eruption (as that actually occurred in 1991 at the cascade volcano of Mount Pinatuba) is reckoned to be between 1.10-4 to 2.10-4/a, that is about one order of magnitude greater than the EBASCO forecast of 1977.

TABLE 2 VEI AND TEPHRA LAYER FOR PROJECTED MOUNT PINATUBO ERUPTIONS [21]
DEPOSITED TEPHRA LAYER THICKNESS AT BATAAN NPP SITE

PARAMETER		VEI 3	VEI 4	VEI 5	VEI 6	VEI 7
COLUMN HEIGHT	km	8	12	25	35	45
EJECTA MASS	kg	5.7.E+9	5.3.E+10	5.4.E+11	2.1.E+12	5.7.E+12
TEPHRA LAYER§	cm	0.005/0.01	0.3/0.5	4.7/8.0	13/26	30/58

§ Tephra layer thickness for regional wind pattern 2006 and taken as a maximum, ie 30/58 – the prevailing wind blows from the north towards the Bataan NPP site.

Of course, the VEI is a compilation and scoring of an event once that it has happened, whereas, to the contrary, planning the robustness of a NPP to withstand a volcanic event challenge requires the *design-basis* parameters having to be determined in advance.

Hazard and Risk Rating: There have been a number of attempts to categorize the risk by various statistical processes, one such example constructs a combined weighted assessment, or scoring, taking into account the *Hazard Rating* and *Risk Rating*, that is essentially giving regard to past eruptive behavior of the volcano and its and proximity to and size of local and regional populations, for example:

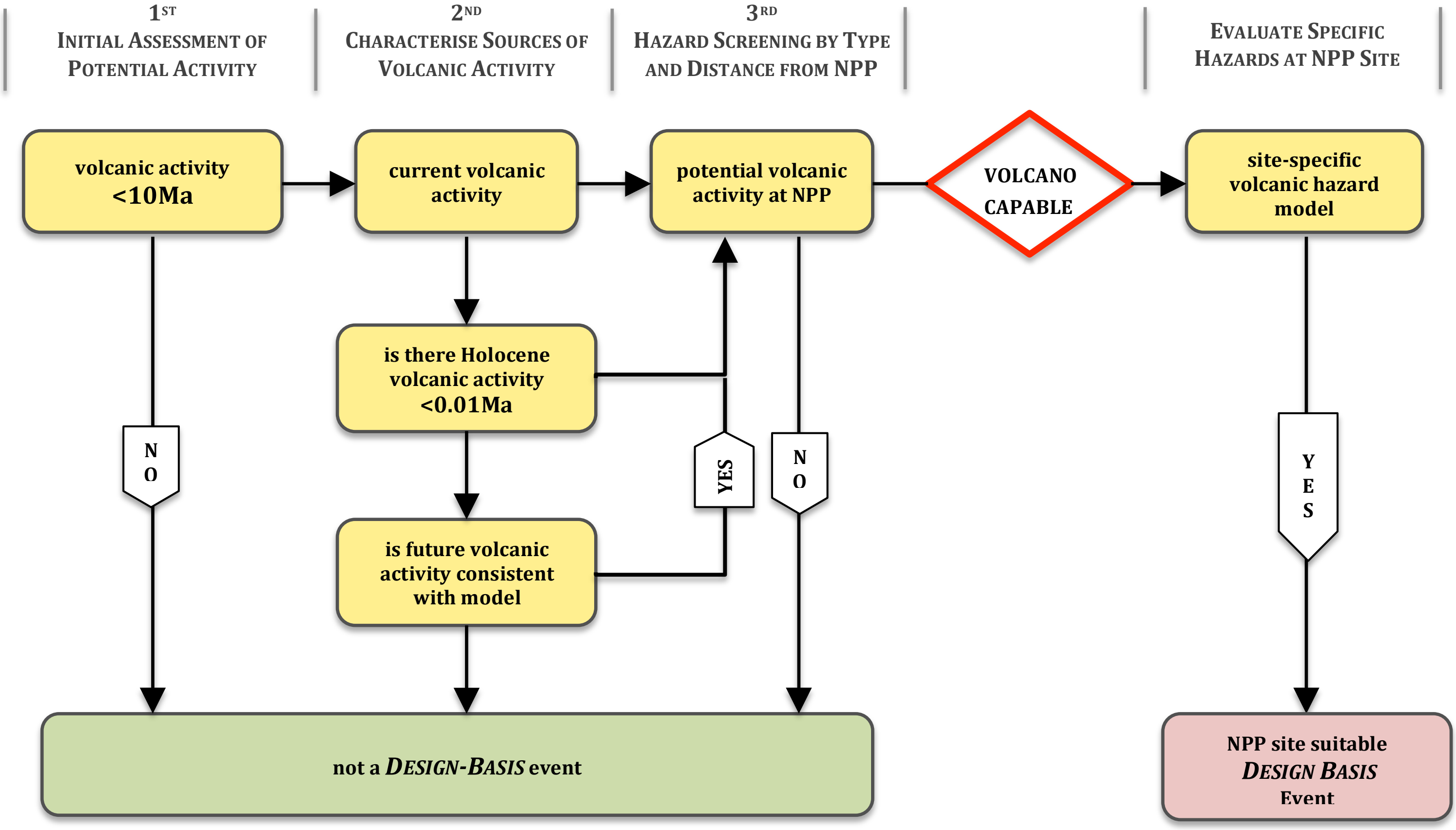
TABLE 3 HAZARD ZONATION AND LONGER TERM FORECASTS[22]extracts

SCORE	15	14	13	12	11	10
PHILIPPINES	HIBOK-HIBOK	MAYON		CANLAON TAAI		BULUSAN
JAPAN (KYUSHU)		**(SAKURAJIMA)**	**ASAMA USU**	**FUJI**	**KOMAGATAKE (UNZEN)**	**BANDAI TOKACHI**
USA (HAWAII)	ST HELENS		(KILAUEA)			LASSEN PEAK (MAUNA LOA) (MONO-INYO)

Methodological Approach: A more practical and, perhaps, pragmatic approach is to adopt a series of step-by-step screening criteria thereby eliminating candidate NPP sites. This method, favoured and claimed by the IAEA to be the methodological approach,[27] follows a sequential assessment of three separate segments of volcanic activity hazard and, from this, evaluates how these might influence the safe and reliable operation of the NPP – the end objective of the approach is to develop a specific volcanic hazard model that, together with the NPP type, its detailed design features and the site and its location, will determine the *design-basis* parameters for one or more volcanic driven events.

The IAEA SSG-21 *Volcanic Hazards in Site Evaluation for Nuclear Installations* is represented schematically as follows:

DIAGRAM 1 IAEA APPROACH TO NPP SITE VOLCANIC HAZARD ASSESSMENT FOR DESIGN BASIS



For its volcanic effect assessment guidance[7] the NRA, although following the principle of the IAEA methodology, sets the first cut-off activity within the Quaternary period (~2.6 million years rather than the IAEA 10 million years past); it retains the second stage Holocene period screening; and for the hazard screening it defines a distance of 160km beyond which any volcanic activity would be most unlikely to present any challenge to the continuing (safe) operation of the NPP – these NRA evaluation and screening criteria are shown in **FIGURE 1** of **APPENDIX I.**

The change of the 1st period from 10Ma to 2.6Ma, on the basis that no volcanic activity has been found during the respective periods, implies that the annual probabilities of future eruptions are less than 10^{-7} per year and $\sim 4.10^{-7}$ per year for the IAEA and NRA screening periods respectively. That said, the general case for Japanese volcanoes is that within the screening distance of most Japanese NPPs there will exist a Holocene volcano and which, therefore, will be classified *'capable'* in terms of the IAEA definition.

The dominant screening criterion for the NRA is the 160km distance which is applied to all volcanic effects (not just tephra ash fall), although unlike the IAEA the NRA sets out secondary screening distance criteria (eg for lava flow a distance of 50km from the NPP site) – see **CHART 1**, **APPENDIX I.**

Neither the IAEA nor NRA seem to accept the determination of an annual probability of occurrence of a particular volcanic event arriving at the NPP (ie a pyroclastic surge) by multiply the probability of occurrence of a volcanic event by the probability that the phenomena associated with the event will reach the NPP site.

Although the NRA adopts the general methodology recommended by the IAEA it differs in a number of important respects. For example, the NRA sets out a universal screening distance of the NPP from the erupting volcano for all effects at 160km over which the volcano will have no significant impact from and volcanic effect. In addition, the NRA separately defines specific distances over which certain volcanic events (ie lava flow) will run-out. In terms of the potential interaction of the volcanic effects with the candidate NPP, the NRA guidance on volcanic effects is ambiguous, particularly on the requirements of the operator to establish the *design-basis* parameters.

PART III - VOLCANOES OF JAPAN

The islands of Japan archipelago are formed on the *'Ring of Fire'*[17] with, first, the islands being formed by volcanic activities in the late Miocene[18] but which are now exhausted. Most Japanese volcanoes have been active since and are of the *stratovolcano* or *complex* form.

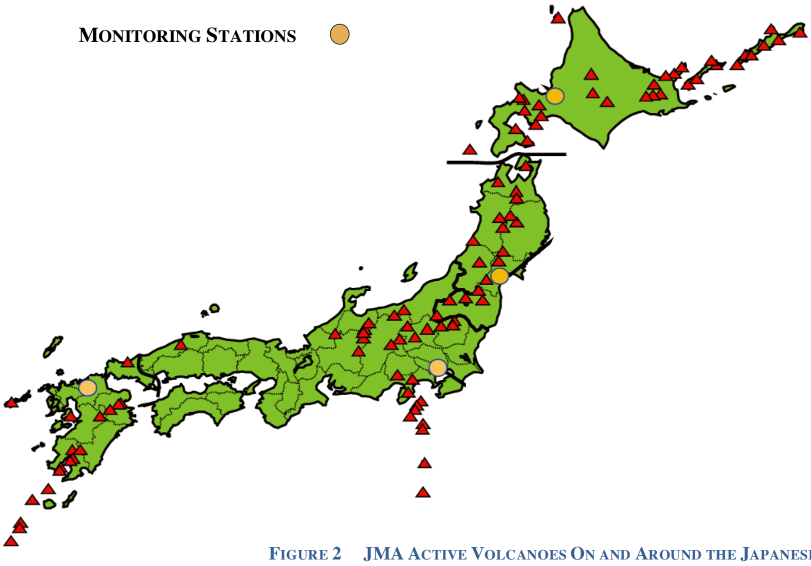


FIGURE 2 JMA ACTIVE VOLCANOES ON AND AROUND THE JAPANESE ARCHIPELAGO – ALL SUBSEA NOT SHOWN

In Japan, the definition of active volcanoes is set out jointly by the *Japan Meteorological Agency* (JMA) and the *Coordinating Committee for Prediction of Volcanic Eruptions* (CCPVE).

The definition of active volcanoes[23] has fluctuated over the years, but in 2003 JMA defined active volcanoes in Japan as '*volcanoes which have erupted within 10,000 years or volcanoes with vigorous fumarolic*[19] *activity*'. On this Holocene[20] screening basis there are 110 or so *capable*[21] volcanoes in and around Japan.

17 The *Ring of Fire* describes the combined regions of mountain-building earthquakes and volcanoes with surround the Pacific Ocean.

18 *Miocene* – an epoch in Earth history from about 24 to 5 million years past.

19 *Fumarolic* – emitting steam and gases.

20 *Holocene* – the period of the past 10,000 years to the present day - as a general guide, volcanoes that have erupted during the past 10 000 years are usually considered active or capable, although many volcanic arcs exhibit recurring volcanic activity for longer than 10 Ma.

21 A *'capable'* volcano or volcanic field is a volcano and/or volcanic field that is potentially capable of producing hazardous phenomena that may affect the site of a nuclear installation.

CCPVE further refined the definition of an *active* volcano into three ranks – A, B and C – each defined by the degree of past activity. However, arguing that past activity was not a wholly reliable portend of future volcanic risk, around 2009 CCPVE replaced the straight ABC ranking system with a programme of identifying and monitoring which of these capable volcanoes could be expected to erupt over the timespan of the next 100 years.

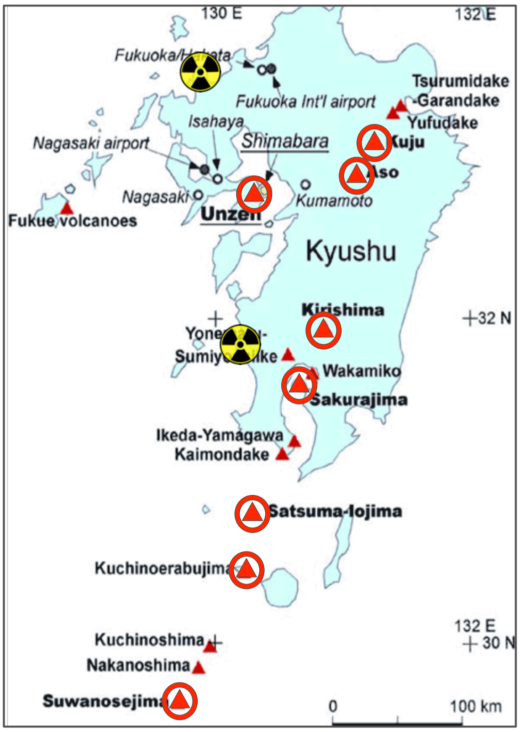


FIGURE 3 KYUSHU VOLCANOES DESIGNATED VAS

This latest reclassification of volcano capability whittled down the active volcano watch list to 47 volcanoes that are presently constantly monitored of which, as of April 2012, a total 29 volcanoes were placed under the *Volcanic Alert Scheme* (VAS).[22] VAS volcanoes located on the southern Japan Kyushu Island are shown by FIGURE 3 (above right) – these are basaltic-andesite volcanoes. FIGURE 3 also identifies the Sendai and Genkai NPPs located on the south-west and north-west of Kyushu respectively.

KYUSHU CAPABLE VOLCANOES

Three of Japan's most active volcanoes are located on the southernmost Japanese Kyushu Island, these are:

Mount Unzen, a complex volcano located to the northwest nearby the city of Shimabara, has a pronounced magma dome the collapse of which has produced recent pyroclastic flows. The eruption of 1792 is believed to have triggered a large tsunami. More recently, Unzen violently erupted in June 1991, forming a pyroclastic flow that spread about 4.5 km from the vent, and since that time there have occurred a number of smaller eruptive and pyroclastic activities until activity petered out in 1995.

FIGURE 4 MOUNT UNZEN - SHOWING THE PYROCLASTIC FLOW TRACK AND LAHAR DEPOSITS

Mount Sakurajima, located in the southwest Kyushu Island is the most active stratovolcana in Japan. The summit of Sakurajima is split into three peaks, one of which the southern peak *Minami-dak* is presently in constant or *persistent* activity with *strombolian* (relatively weak) eruptions, the latest of significance being in September 2014. In the past, very significant eruptions occurred during 1471-76 and in 1914, with the latter following a year of repose. This complex stratovolcano has reformed its active caldera several times, with the present caldera is formed on the southern rim of the 17 by 23 km wide caldera of around

FIGURE 5 MOUNT SAKURAJIMA - FOLLOWING THE EXPLOSIVE ERUPTIONS OF SEPTEMBER 2014

22 Since 2012 the number of volcanoes of the VAS may have increased under the programme of VAS implementation.

The Shinmoedake volcano is part of the Mount Kirishima cluster of volcanoes about 25km west of Miyakonojo. Significant eruptions from Shinmoedake are recorded for the years 1716-17, 1822, 1959, 2008-9 and most recently in February and March 2011.[24]

Comparison of recent Shinmoedake events provides a very crude gauge of successive eruptions even after a relatively short period of repose. For example, ash fall during the 2008 Shinmoedake subplinian[23] eruption, itself lasting several hours, was an estimated tephra ejecta mass of 200,000 tonnes.[25] This compares to the 2011 eruption, that included a number of vulcanian[24] events, during which the total ash fall was estimated to be between 6.6 to 12 million m^3 of dense rock equivalent (DRE).[26][25]

FIGURE 6 MOUNT KIRISHIMA - ERUPTION AND ASH CLOUD FROM SHINMOEDAKE IN FEBRUARY 2011

VOLCANIC ACTIVITY WARNING SYSTEM

The Japan Meteorological Agency issues *Volcanic Forecasts* when a volcano becomes active.

The *Volcanic Alert Scheme* or VAS for each volcano comprises five stages[26] depending on *'the areas that must be warned'* and *'the response that should be taken'* for the present state of unrest (activity) of the particular volcano - although the VAS is primarily for safeguarding members of public,[27] there is no doubt that its warnings will be relayed to and taken into account by operators of NPPs in the vicinity and region.

The VAS is updated whilst the subject volcano remains active – these updates are accessible to members of public and other stakeholders (see Kyushu right).[28] Similarly, for active volcanoes there is an Ash Advisory web service.[29]

FIGURE 7 JMA VAS UPDATE FOR KYUSHU

23 Subplinian Eruption – a steady, continuous and energetic eruption.

24 Vulcanian Eruption – a short, explosive or blast-like eruption lasting a few seconds or minutes.

25 The tephra ejecta volume for the 2011 Shinmoedake eruption was about 1% that ejected by Mount St Helens in the United States in 1980.

26 VAS Level 1 signifies that no particular response or action is required; Levels 2-3 indicate that, while residential areas are not threatened, the volcano is off limits for hiking or climbing; Levels 4-5 reveal that residential areas are starting to be threatened by the danger of eruptions – VAS should not be confused with VEI.

27 Level 4 is the stage where people with special needs are evacuated and other local residents prepare to evacuate, and at Level 5, all local residents are subject to mandatory evacuation from threatened areas. Ash Fall Forecasts are issued by JMA for eruptions exceeding a certain magnitude and to those forecast areas likely to be affected by ash fall up to about 6 hours after the eruption.

28 http://www.jma.go.jp/en/volcano/

29 http://ds.data.jma.go.jp/svd/vaac/data/index.html

PART IV – VOLCANIC HAZARDS AND THE RISK TO NUCLEAR POWER PLANTS

DETERMINATION OF THE HAZARD ZONES

As previously noted, the IAEA provides a guide[27][30] to the hazard identification and zoning processes to be used mainly in the site selection and evaluation for new nuclear installations, although it may be used for retrospective assessment of existing NPPs. Application of the IAEA guide will be considered later in this Review, particularly in its application to the Sendai NPP volcanic safety case and its compliance with *'The Assessment Guide of Volcanic Effects to the Nuclear Power Plant'*. [7]

Generally, volcanic activity hazards zones relating to the various volcanic activities described in **PART II** are, first, defined in *proximal* and *distal* terms;[31] secondly, these hazards are screened via the magnitude of the hazard effect; and then, third, assessed in terms of if and how each particular hazard, singly or in combination with others, might challenge the buildings, structures and functions of the specific NPP under consideration.

Although certain of the **PART II** hazards are within striking distance of the two NPPs located on Kyushu, this Review is primarily concerned with tephra fall on and around the proximity of the Kyushu Electric Sendai NPP. That said, the other volcanic hazards identified should not be ignored and similar consideration should to be given to other Japanese NPPs and nuclear facilities that are also located proximate to capable volcanoes.

TEPHRA FALL

Atmospheric dispersion and eventual deposition of tephra is determined by a number of factors, including ejecta plume height, the temperature of the air, total mass of tephra ejected, ash particle size, buoyancy and settling or deposition velocity, atmospheric stability, precipitation and wind direction. These factors define the shape and size of the ground footprint and the rate of deposition of the falling tephra.

The general rule is that the tephra deposit decreases in both thickness and particle size the further away from the source – that is although grain or particle size distribution is mainly determined by the height of the eruption column and velocity and direction of the wind, there is a general tendency for coarser material to accumulate in proximal areas, while finer material is carried to distal areas.[28]

Preserved in the geological record is a chronology of past volcanic events: The outcome of a energetic vulcanian, plinian or sub-plinian eruption is that large fragments, thick pumice and/or scoria are likely to accumulate in the immediate vicinity of the vent, particularly around the foot of the volcano – these deposits are generally preserved over time – whereas the finer ash particles and slithers (generally of diameter less than 2 mm) are carried aloft with the erupting plume for dispersion and eventual deposition farther afield – the geologic

30 IAEA Specific Safety Guide No SSG-21, 2012 supersedes IAEA PSSS-01, Volcanoes and Associated Topics in Relation to Nuclear Power Plant Siting, 1997

31 Proximal/Distal – near to and away from the centre of the eruption respectively

record for these more widely dispersed component of the ejecta may not, however, present a distinct geological record. This is because the depositing tephra is fine grained and easily reworkable; if the eruption volume (even of successive eruptions) is not large then the tephra will mix with soil and become obscured; but if a single eruption event is sustained for a long period, the ash fall will accumulate and form a distinctive layer.

For these reasons, the geologic record of past volcanic events, particularly ash fall, deserves careful interpretation.

MODELLING TEPHRA AIRBORNE DISPERSION AND DEPOSITION

The airborne dispersion and deposition of ejected tephra can be modelled in advance of and/or whilst the eruption is underway. There are a number of software packages developed and proven for this task, such as TEPHRA2 in use by JMA – most of these mathematical modeling programs derive from the work of Suzuki in 1981.[29]

Limitations inherent in all mathematical representations of complex geologic processes arise because of incomplete knowledge of details of complex and heterogeneous natural processes involved in volcanic eruptions, including use of a mathematical representation that approximates, but does not specifically represent, every detail of the process; and lack of comprehensive data describing every aspect of the complex, heterogeneous geologic natural processes being represented. As a result of these limitations, mathematical modelling provides predictive capability but not an exact representation of the process nor its outcome (ie the location and amount of tephra deposited).

During a strombolian eruption ejection of magma into the atmosphere is a ballistic fountain of µm and mm-size particles elutriated from larger scoria fragments carried up into the plume by the eruption energy and rising convective hot air and gases of the plume stalk. Whereas the remaining larger ballistic and scorer fragments deposit around the vent orifice, the convective plume provides a source for distal transport of potentially tephra ash downwind over a wide area. Fallout of ash from the plume forms a ground layer that generally thins with distance from the vent and is subject to redistribution by wind and water erosion. With increasing eruption violence, a larger fraction of the magma is fragmented to ash sizes, and a greater proportion of the magma contributes to the convective plume. Generally, mathematical models are limited to representation of the plume alone requiring input direction to define the proximal-distal ejected mass distribution.

Mathematical models solve diffusive transport (by atmospheric turbulence and wind) of particles distributed in a column (plume) of a height determined mainly by the heat flux (power) of the column source. The duration of this transport for individual particles is the fallout time governed by the particle's terminal fall velocity (a function of the particle individual size, density, and shape factor) and their upward velocity in the plume. Models usually assume a linear falling away of the plume rise velocity, from a maximum at the vent mouth to zero at the top of the plume, thereby neglecting buoyancy-driven velocity contribution.

Another general limitation is the inability to accurately represent the transport of tephra particles of mean diameter less than approximately 15µm with this artificial cut-off in mean particle diameter being the lower limit for the importance of gravitational settling - for particle sizes <15μm, atmospheric turbulence would tend to keep the particles aloft longer than would be estimated by the model – there is a tendency to overestimate the deposition of the finer ash particles closer than further downwind by tens if not hundreds of kilometres downwind. Another limitation is that the mathematical models do not consider ash particle aggregation within the plume (and in some models nor removal of particles from the plume by rainfall) – ash aggregation of particles <15μm would generally compensate for the lack of account of gravitational settling.

Models of a higher degree of sophistication treat meteorological inputs, such as wind speed, shear or profile and direction, as uncertain parameters - the stochastic treatment of wind speed, etc., captures the uncertainty that exists in future wind speeds at all altitudes of the vertical eruptive column. Similar uncertainties are typically assumed for eruptive power and initial rise velocity, which are, in turn, functions of total erupted volume and duration. Assuming a condition in which magma is fragmented and enters the convective plume, the initial plume rise velocity can be derived using a relationship between power, duration, and conduit diameter.

In circumstances where the tephra plume is somehow joined and mixed with an atmospheric radioactive release,[32] the subsequent dispersion and deposition could be modeled using an existing software suite such as ASHPLUME.[30]

a) Tephra Depositon Layer Thickness

FIGURE 8[33] shows the tephra fall deposition layer thicknesses accruing from past eruptions of the Cascade Range of volcanoes (USA).

Referring to **FIGURE** 8, the data for the Mazama eruption (~8,800 BP of total tephra ejecta ~40km³ DRE) and Glacier Peak (~11,000 to 12,000 BP) eruptions are historic with the tephra thickness being compacted, if not eroded and modified over time, compared with the recent St Helens (1980, ~1km³) tephra layer which is uncompacted. The general consensus is that originally the compacted tephra layers would have been twice or more the compacted thickness.[31]

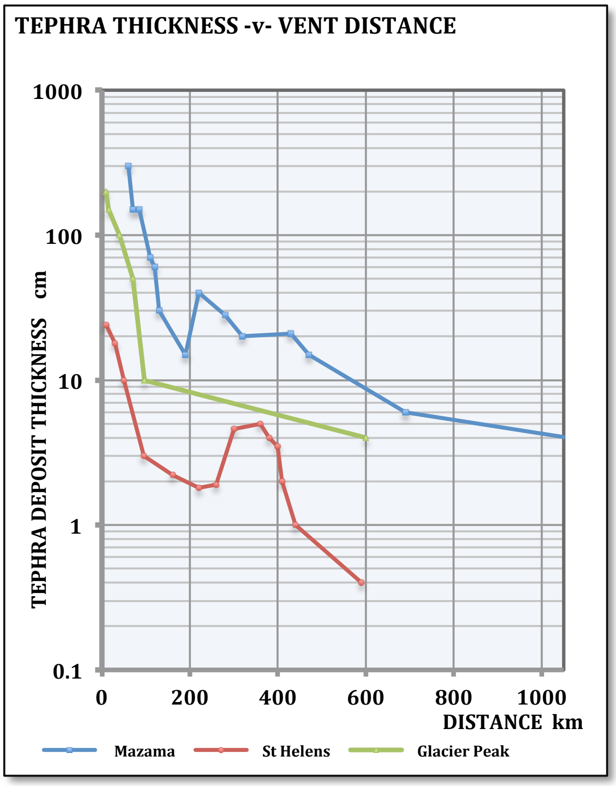


FIGURE 8 PAST EXAMPLES OF TEPHRA FALLS

Ash fall forecasting is routinely undertaken by numerical simulation via any one of a number of advection-diffusion software programs, such as TEPHRA2 and the JMA Ash Fall Forecast.[27] In a modeling process known as *'inverting tephra fallout'*[32] it is possible to gain some understanding the eruptive behaviour of past events, thereby

32 Say where there occurs an atmospheric radioactive release from a NPP whilst there is a volcanic tephra plume dispersing overhead.

33 **FIGURE 8** is a diagrammatic representation of Figure 3-1 of [35].

building up a useful backlog of data for deterministic analysis of potential future volcanic activity.

Prediction of airborne dispersion and deposition of tephra is a complex science in which many variables, including variation of particle size and can be particularly influenced by advection, with humidity being another important parameter.[33] However, at the finer extremes of the tephra particle size, the thickness of the tephra deposits shows a lack of correlation between increasing distance and reducing ash size.[34]

The tephra layer thickness data for the recent Mount St Helens fallout show the presence of a zone of increased layer thickness, rising from about 1.5 to 5cm at about 300 km from the volcano vent (**FIGURE 8**). This is due to the aggregation of very fine ash into larger particles, probably arising from an atmospheric anomaly, with the larger amassed particles assuming a higher descent velocity. Much the same effect occurred during the Mount Mazama eruption of around 8,800 BP but for this more energetic event might result in an uncompacted tephra deposit of about 50cm at a distance of 300km.[35]

FIGURE 9[34] shows the probability of tephra fall layer thickness with distance from the eruption vent, suggesting that at only 10% of the eruptions does the thickness exceed 55cm at 100km distance from the vent. This probability data is drawn from 36 eruptions with tephra fall volumes each equal to or greater than about 0.1km^3 although some bias has been introduced to include for larger eruptions.[36]

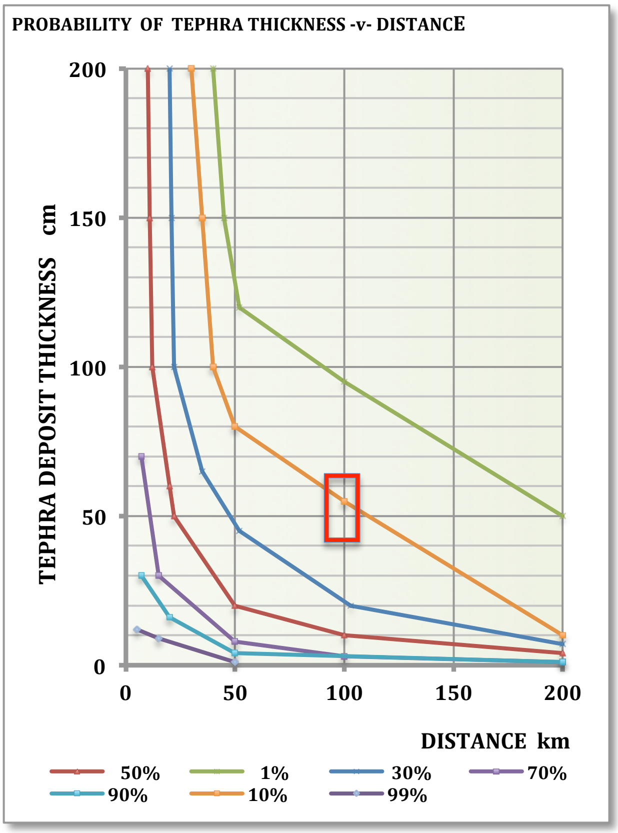


FIGURE 9 PROBABILITY OF TEPHRA FALLOUT THICKNESS

It is also possible to estimate the total ejecta mass from study of the developed plume for explosive events, although this modeling approach is under development.[37]

b) Rate of Tephra Layer Build-Up

The historic record provides no meaningful date relating the rate of tephra deposition during and in the immediate (short term) period following the eruption. Recently witnessed tephra deposition events, such a Mount St Helens in 1980, provide the very limited database for this aspect of tephra fallout.

For the 1980 St Helens event, the ash fall rate is reported to be 1.3cm/hr for a total deposit of 4.5cm of ash at a distance of about 50km from the vent, although it is reasoned that the greater part of this ash layer build-up occurred over the first hour.[38]

34 **FIGURE 9** is a diagrammatic representation of Figure 2.9 of Tlling I R, *'Volcanic Hazards* , Int Geological Congress, Washington, 1989 – see Scott E W, *'Volcanic-Hazard Zonation and Long-Term Forecasts'* p19

The rate at which tephra will accumulate during a fall depends on many factors, including mass-eruption rate, height of the eruption column, wind direction and speed, and distance from the volcano. Estimates of duration of fall, rate at which tephra accumulates, and duration of periods of darkness and poor visibility can be derived from records of historical eruptions.

Information on tephra fall rates can be obtained from measurements made during historical tephra falls, although these measurements are few and the rates are generally averages.

There are records, however, that enable compiled data on the duration of darkness that accompanied some historical eruptions and the total thickness of uncompacted tephra that accumulated at the area(s) of the recorded darkness. If most of the tephra fell during the time of darkness, the mean rates of accumulation vary from less than 1 to almost 20 mm/hr with these values being for total tephra thicknesses that range from 1-300mm depth.[39]

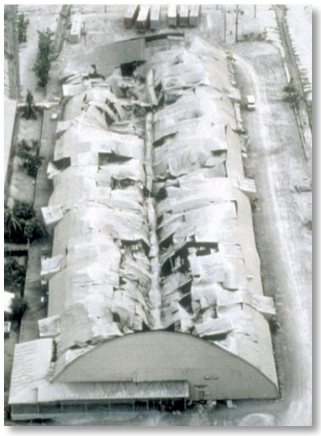


FIGURE 10 COLLAPSE OF A WAREHOUSE ROOF

c) **Tephra Fallout and Nuclear Facilities – General Case**

In general:

i) SUPERIMPOSED LOAD BEARING STRENGTH OF STRUCTURES

Damage to buildings and building components from the loading imparted by volcanic ash or tephra accumulation can range from partial to complete roof collapse. This superimposed (static) loading of roof and other exposed parts of building structures increases directly with thickness of the tephra.

Dry, uncompacted tephra, comprising mostly glass and pumice shards falling at distal localities, has an average density of about 0.5 g/cm^3 but rainfall wetted tephra will rise in specific density to 1.25 to 2.0 g/cm^3 or thereabouts. Uncompacted layers of Tephra accumulating near the volcanic source, say within 20 to 30km, will have a higher specific density similar to lithic-crystal ash.[40][41]

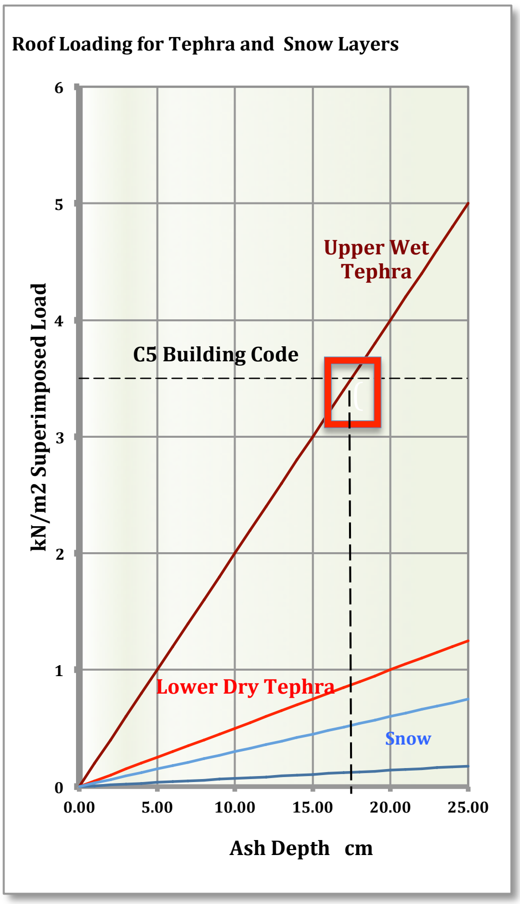


FIGURE 11 TEPHRA ASH AND SNOW LOADS

FIGURE 11 compares the tephra and snow imposed loads for increasing layer thickness – a sample snow loading limit of 3.5kN/m^2 is typically adopted in the design of Japanese built structures, using the Japanese Building Code,[42] is shown thus (----).[35] The design code roof snow loading for the notional building is exceeded when a wet tephra layer thickness reaches about 17cm.[36, 37]

35 It may be that the Sendai NPP building design adopted a higher superimposed load rating – the actual rating is not known.

36 This calculation is based on the 100 year snowfall for the Kyushu Sendai area,

An increase of the superimposed load acting on a built structure will also influence the dynamic reponse of the structure to seismic forces. A rain sodden tephra layer is likely to behave quite differently to a snow cover, being not only denser but also of greater adherence to the building surfaces and therefore less likely to shed from the building during a seismic event.

ii) LOCALISED FLOODING

Roof gutters, drains and downpipes are vulnerable to blockage by wet ash – at times of heavy rain blocked roof drainage can result in water pooling and a corresponding increase in the superimposed roof loading. Ash can also impede and block surface area drainage, and open watercourses may deliver large quantities of tephra and other debris from land areas nearer the volcanic vent, resulting in flooding of large areas of ground.

iii) ELECTRICAL EQUIPMENT[43]

Wet, volcanic ash is sufficiently conductive to cause arcing, *'flashover'*[38] and *'short-outs'* when deposited as a fine, adhering film on conductors and insulators of powerlines and electrical transmission and distribution equipment.[44]

Typically within or nearby the NPP site is a concentrated array of voltage control, protection and switchgear equipment, the substation, serving as the connection node between the NPP and the off-site electrical distribution network. Substation equipment is susceptible to capacitance flashover and other failures because of the insulators are situated at low height or at ground level where localized wind eddies and other ground effects might serve to increase ash accumulation and retention, where switchgear and circuit breakers might seize when covered with abrasive ash, and transforming equipment overheat if the casing cooling fins are clogged with excessive ash fall.

FIGURE 12 FLASHOVER

Insulator flashover is the most common impact on electrical networks from volcanic ash fall, and may arise across generation, transmission components and distribution networks, especially when the ash fall is accompanied by a light mist and/or drizzle.[45] Failure of the regional transmission, local distribution[39] and/or NPP substation might bring about a loss of offsite power (LOOP) leaving the NPP electrically stranded and dependent upon the on-site emergency electricity generation to maintain essential power supplies, especially for post-trip reactor core and spent fuel pond cooling.

37 Kyushu Electric state that the allowable superimposed load for the Sendai NPP nuclear island, emergency generator and other essential services are higher within the range of 4.4 to 9.8kN/m^2.

38 When dry, ash typically has a low conductivity (high resistivity) to electrical current, but when wetted, the soluble salts on the surface are mobilized and lower the resistivity. Many factors influence flashover potential from volcanic ash contamination, including grain size, soluble salt content, ash fall thickness, shape and composition of exposed components, network configurations and weather conditions before, during and after the event. Because flashover is more prevalent with finer grained ash, failures of the electricity grid distribution and supply systems may occur at distal locations. – see [43] for a detailed exposition on this and related infrastructure topics.

39 Experience from impacts of the 1980 eruption of Mount St Helens volcano on electrical networks [44] suggests that transmission networks are generally less vulnerable to ash-induced flashover than distribution networks. Transmission networks (110–500 kV) were able to withstand ash falls of 6–9 mm before serious flashovers occurred. However, on smaller distribution networks (33 kV) and domestic supply voltages (400 V) which received the same thickness of ash, flashovers were a more common problem, leading to sustained power outages of the higher order transmission system for several hours or longer.

Volcanic eruptions inject considerable quantities of water vapour (H_2O) and, depending on the source magma, carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrochloric acid (HCl), hydrofluoric acid (HF) and ash into the atmosphere. Of these, HCl and HF dissolve in water and fall as acid rain whereas most SO_2 is slowly converted to sulphuric acid (H_2SO_4) aerosols. Surfaces covered with moisture sodden tephra are prone to erosion and corrosion, although such is a relatively slow process of little or no immediate impact.

The presence of acid rain is irritable to the skin and eyes and may frustrate essential and emergency services personnel engaged of priority actions, such as electrical distribution equipment repairs and cl;earance of tephra laden roofs and tank tops.

iv) NUCLEAR POWER PLANT GENERATION SITES

General impacts of volcanic ash fall on NPP generation sites can include flashover in substation yards, see iii) above; ash penetration into buildings which may damage sensitive machinery and electronics; damage to essential water services pumping machinery and heating, and ventilation air conditioning (AC) systems; clogging of filters and strainers; and structure failure such as the collapse of long span roofs, and the possibility of progressive collapse of floors below.

Potential damage modes arising from ash fall relate to the composition of the tephra, particularly the range of particle size[40] presented with regard to filter clogging; the hardness[41] of the particles relating to abrasion of pumps and other machinery with close moving parts; and the chemistry[42] particularly with regard to its adherence on surfaces (such as glass and porcelain insulators) and aggregation and combined density, particularly when borne in water cooling systems.

More specifically:

1) **Air Filters - Nuclear Island Building Containment and Essential Service Areas Ventilation and Purge**

APPENDIX III shows, for a typical light water reactor (PWR) NPP the air ventilation and purge systems for the reactor containment, essential services (spent fuel pond) building, and the emergency diesel generator and water intake screen buildings – a typical NPP would have a number of other controlled ventilation systems servicing further buildings and processes.

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40 Tephra particles vary greatly in size, ranging from a mixture of large to small particles near eruptive vents, to very fine particles at long distances. Glass shards of about 2mm equivalent aerodynamic diameter ranging as small as about one-tenth of a micrometer are common in downwind ash in the distal zones.

41 Of a typical tephra composition: Pumice is a highly voided, mainly of glass low density (0.7 to 1.2g/cm^3) composition of about the same hardness of glass at about 5 Moh, a little softer than the blade of a steel knife – Glass shards are of higher density (~2.4g/cm^3) at 5 Moh – Lithic fragments are dense (~5 to 7g/cm^3) about 7 Moh, equivalent to a high quality steel knife blade – Crystalline Fragments are typically coated with magma glass ((~2.5 to 5g/cm^3) of about 5 to 7 Moh.

42 Tephra glass and crystalline minerals are relatively inert and decompose slowly under the normal climatic conditions although fragments may be coated with soluble salts and liquid condensates from the eruption – when moist these salts may mobilise to improve the adherence of tephra thin films to smooth surfaces, such as glass and porcelain insulators.

Tephra particle intrusion into the sliding and/or exposed parts of machinery, such as air moving cyclones, pumps and fans can result in erosion, fouling, overheating and seizure.

In the **Appendix III** example of the reactor building ventilation (1st diagram) there is no provision for filtration at the intake stages for the *purge and vent air supply* and the *outside air dilution*. During ash fall, tephra laden air would be drawn into the ventilation and purge systems placing at risk downstream filters and components, particularly exposed to fouling and seizure are the containment ventilation exhaust fans that handle up to 33,000 cubic feet per minute (~1,000m^3/min).

Other than the general observation that air filters will become blocked under tephra fall, there is little information and data on how quickly and the degree of blockage that will impede specific functions throughout the NPP, as this is will determined by, for example in ventilation systems, the specific air handling rate for each particular system and process. In the open literature there are a number of citations that recommend changing vehicle air and oil filters at 4 hourly intervals to protect against engine failure;[46] the US military give a particular regard to changing filters on vehicles, ventilation and computer systems, including vehicle and static generator engine fuel filters (as volcanic ash laden air will be drawn into the fuel tank via the air equalizer vents as it empties), generally at every 1½ to 3 hours of continuous running.[47]

2) Air Filters – Emergency Diesel Generator Buildings

Prime moving equipment, such as gas turbine and/or diesel sets powering emergency generators (necessary in the event of a LOOP) and, where temperatures are high, for example at the exhaust valve passages of a diesel motor and in the combustion chamber of a gas turbine, particle fusion - these aspects require filtration at the air intake cowl (see right),

FIGURE 13 DIESEL GENERATOR INTAKE PRE-FILTER COWL

The emergency generator fan blown cooling coils, serving engine and generator and, separately, the engine lubricating oil, are often mounted on the roof of the emergency generator buildings, also require protection against the accumulation of tephra in the cooling coils and fins (ie radiators) and protection of the fan motors against abrasion and seizure.

Since 1991, the United Stated Nuclear Regulatory Commission (NRC) has required NPP that *'. . . volcanic activities should be assessed as part of the IPEEE process at plant sites in the vicinity of active volcanoes. . .'*, [48] with this requirement being assessed and specified on a plant-by-plant basis.

The Columbia NPP,[43] design-basis *Abnormal Condition Procedure ABN-ASH*[44] for a tephra fall event directed reducing power, scramming the reactor, and cooling down to cold shutdown. The limits triggering reactor shut down defined in ABN-ASH design-basis were, either, i) an ash cloud at an altitude of 40,000 feet (~12,200m) or higher,

43 The Columbia PWR NPP is about 220km and 165km to the east of the Mount St Helens and Mount Adams volcanoes respectively.

44 Energy Northwest, Abnormal Condition Procedure ABN-ASH ME-02-87-95 – this is not a publicly accessible document although details of which are cited in [51]

expected to begin passing over the Columbia NPP site within two hours and drop ash for up to 20 hours, or ii) an ash fall rate exceeding 0.21 in/hr (~0.53cm/hr).[49][50]

There have been a number of NRC violations issued against Energy Northwest, the operator of the Columbia NPP, relating to both the emergency generator combustion air intake filters and, separately, the emergency generator room ventilation outside air supply filters[51] both of which related to management procedures for alternate running of the two on-site generators, although of interest here is the filter change times in account of clogging by ash fall.

For the combustion air intake filters (see **FIGURE 13** for example) the filter would clog and need changing after 2.3 hours runtime. The emergency generator room heating, ventilating and air conditioning filters (see **APPENDIX** III)[45] would need changing every 3.6 hours of runtime.[51]

In other words, in an ash fall event the Columbia NPP would be required to shut down nuclear generation operation and remain shut down for the (hypothetically) specified ash fall duration of 20 hours. If during that period of shut down, the regional or local transmission electricity grid itself failed, say because of ash fall triggered capacitance flashover, then the NPP under LOOP conditions would be entirely dependent upon on-site generated power from its emergency generators for essential services, reactor core and spent fuel pond cooling. During the extended period of emergency power generation, each of the two on-site generators would have to be shutdown whilst the combustion air intake and room ventilation filters were changed. For the room ventilation filter change, a temporary alternate filter would have to be jury-rigged to protect the generator running at the time of the ventilation filter replacement. Ash loading on these filters could result in a common-cause (ie common-mode) failure of the emergency diesel generators due to insufficient combustion and/or room cooling air flow.

3) **Condenser Seawater Inlet and Circulation Pumps**
Essential Services Water Supplies and Pumps
Emergency Cooling and Make-Up Water Pumps[52]

At various localities around the NPP considerable volumes of water are pumped and directed to various processes, mainly for cooling during normal operation and for emergency cooling and water make-up during certain abnormal and/or accident events.

a) <u>Steam Circuit Condenser Cooling</u>

The main water pumping activity is to cool the turbine condenser that serves to reduce the exhausted, low pressure steam to water for pumping back up to steam pressure – a typical 1,000MW_e NPP will pump between

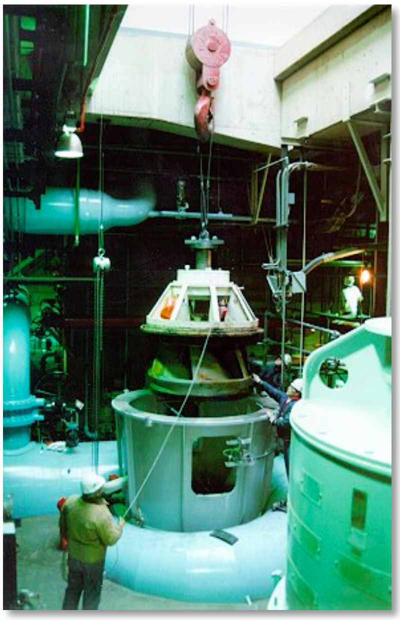

FIGURE 14 A MAIN CONDENSER COOLING PUMP, USUALLY ONE OF FOUR PUMPS

45 But note this example does not show ventilation air intake filters – at Columbia the emergency generator room air ventilation filters were in the flow path op the combustion air filters.

2,000 to 2,750m^3/min depending on the temperature rise of the exhausting water.

The condenser cooling stream will be directly drawn from the sea for coastal sites or from a river or lagoon for inland sites – these are both *once-through* systems where the returning (hot) condenser cooling water is dumped back into the extraction source. Some inland NPP sites utilise water cooling towers within which the condensate is spray-cascaded down over a series of slats or louvres to achieve the necessary cooling before being returned and recycled in the condenser – these *closed-loop* towers, either hyperboloid naturally drafted tall towers, or the more compact towers with motor-driven fans, require continuous make-up water to compensate for the high evaporative losses of the cooling process.

The electrical motors driving the condenser (and other) pumps also require cooling. Typically, this is achieved by a closed recirculatory air system passing over the electrical motor coils and fields, which is cooled by an secondary open air circuit – depending of the detail design, this secondary circuit may be prone to failure by abrasive tephra ash entry into its fan bearings and blockage of the heat transfer surface (typically fins).

b) Essential Services Cooling: NPPs also require water for cooling other essential services and, again dependent on the particular NPP site, extract water from the appropriate nearby source, be it the sea, river or inland lagoon. The extraction rate varies with season and ambient conditions with a typical 1,000MW$_e$ extracting between 150 to 200m3/min in addition to the very much larger rates of extraction for condenser cooling.

Depending on the particular NPP design, the essential service water system routes this water to plant equipment such as the chillers for air conditioning units,[46] lubricating oil coolers for the main turbine, aftercoolers for air compressors, and heat exchangers for closed-loop cooling systems providing cooling water to other equipment such as the spent fuel pool heat exchangers. Many of these essential services and processes require continuous cooling even when the nuclear plant is shut down and has been so for some time (eg the spent fuel pond).

c) Emergency Cooling and Make-Up Water: When, as the result of some abnormal event, the reactor undergoes SCRAM (automatic rapid shut down) and with the turbo-alternator tripped, the heat remaining in reactor core and primary circuit has to be very quickly dissipated or dumped to the ultimate heat sink (UHS) to avoid reactor fuel core meltdown and a heightened risk of radiological release.

Depending on the particular NPP design and site location, the UHS can be an adaptation of the sea, river or lagoon source from which the condenser cooling is extracted and discharged, and/or a separate UHS such as banks of flash evaporators or sprays discharging and recycling into dedicated UHS pond.

46 Heating, ventilation and air conditioning (HVAC) systems are essential for a healthy working environment inside inhabited buildings and, particularly, for maintaining critical components of infrastructure in working order. Many electronic control systems cannot function without external cooling, due to the heat generated by internal computers and electron processing – for example, most telecommunication exchange and mobile cell facilities require constant air conditioning. Air conditioners are known to be vulnerable to ash blockage, corrosion and arcing of electrical components, and air-filter and heat transfer coil blockage.

The reservoirs used in all of the water abstraction for the condenser cooling, essential services and emergency cooling processes are vulnerable to tephra contamination from ash fall - ash settling on the surface of the intake water reservoir and combining as vesiculated *'pumice rafts'* will foul and block the intake screens; waterborne ash particles carried into the pumps delivering the water to various essential services processes may seize the moving parts of pumps by abrasion; and, waterborne particles might settle out across banks of heat exchanger tubes thereby impairing the heat transfer process.

There is very little in the open literature to relate how, if at all, the NPPs located within the tephra deposition footprint incorporated design features to facilitate continued operation is such a hostile environment and, indeed, since no NPP to date (other than the defunct Bataan NPP) has been subject to a significant ash deposition, there is no operational experience to relate how the NPP would fare.

v) INTER-RELATED EFFECTS ON- AND OFF- THE NPP SITE

Ash fall and other volcanic activities are widely distributed assaults on the infrastructure – the impact and consequences are also likely to be widespread and diverse.

Obviously, a thorough assessment of potential hazards to NPPs needs to be undertaken on a site-for-site basis, taking into account site-specific factors such as plant design, air and water supply, site, staff, emergency personnel, vehicles, and surrounding environment. Also, the situation may persist for days and weeks, indeed for longer, if tephra fallout from successive, closely spaced eruptions continues, thereby exacerbating the situation.

a) Access to the NPP Site: Falling ash will significantly reduce visibility, in some instances to near total darkness. Moving vehicles along ash covered roads will stir up and resuspend ash creating billowing ash clouds adding to the visibility hazard. The deposition of fine, hard ash particles on road surfaces may reduce traction, particularly when the ash becomes wet. Ash deposits thicker than 1 mm will obscure markings on roads that identify lanes and road shoulders. [53]

FIGURE 15 RESUSPENSION OF TEPHRA SURFACE LAYERS BY VEHICLES

Airborne transport, particularly helicopters, may be grounded and unavailable because of the detrimental impact of airborne ash on gas-turbine components.[54] Electricity transmission and distribution faults may be inaccessible to cross-country repair and maintenance crews, leaving the NPP in LOOP. Similarly, there might occur damage to telecommunication equipment (aerials, antennae, dishes and masts) and communications generally might be disrupted by high user demand.[53][45]

b) NPP Staff Availability: Staff and emergency personnel may not be able to gain access to a NPP if vehicles fail or roads are impassable and, moreover, specialized emergency services personnel may be prioritized and committed elsewhere. NPP service and maintenance personnel responsible for reactor operation and safety may not be able to perform their duties because of difficulties with breathing and vision. Indeed, NPP personnel may be unwilling to leave their families and homes in such an emergency.

PART V – SENDAI NUCLEAR POWER PLANTS – VOLCANIC RISK DESIGN-BASIS

SENDIA NUCLEAR POWER PLANTS

At Sendai, the NPPs comprise 2 pressurised water reactors (PWR) owned and operated by the Kyushu Electric Power Company. Each reactor primary circuit is a three-loop, type-M designed and built by Mitsubishi Heavy Industries, being commissioned to full power in July, 1984 and November 1985 respectively.

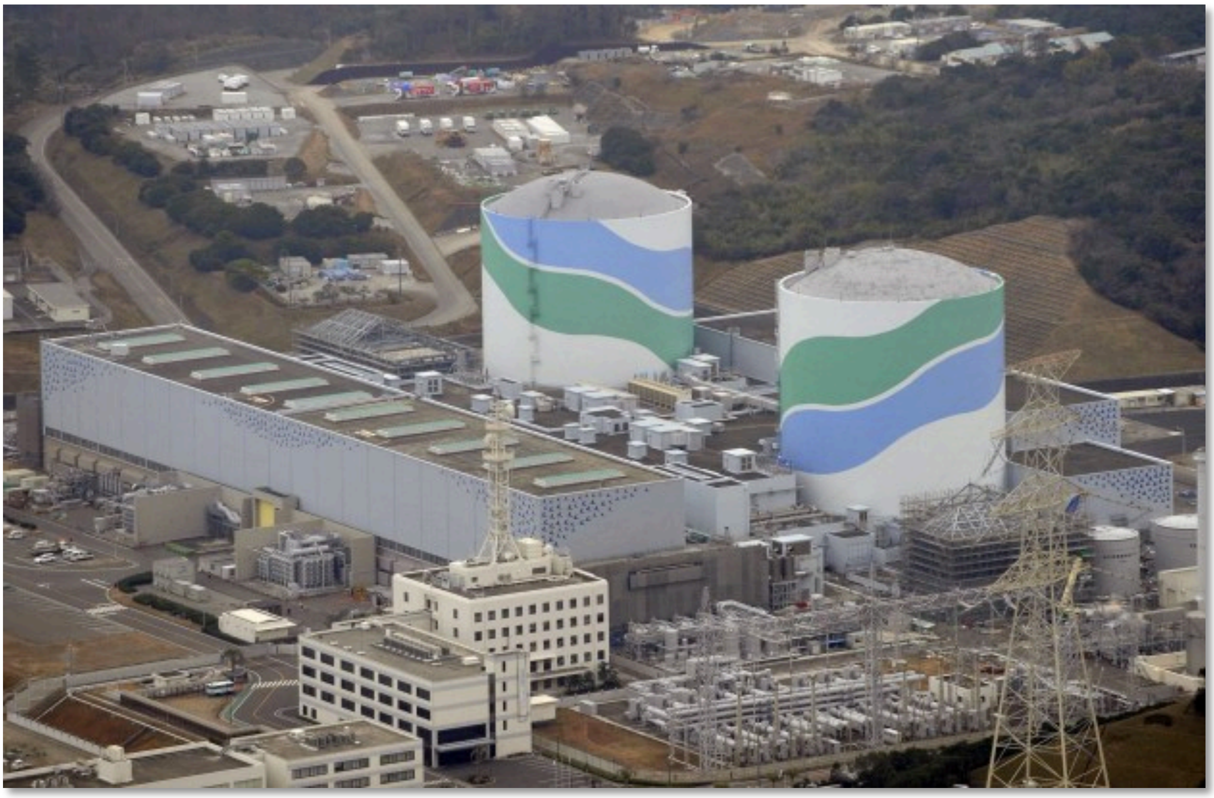

FIGURE 16 SENDAI NUCLEAR POWER PLANTS

The two Sendai NPPs are located on a single site in the Kagoshima Prefecture of the southern island of Kyushu, at the mouth of River Sendai about 12km east of Satsumasendai City (pop ~100,000).

Following the Fukushima Daiichi catastrophe of March 2011, both Sendai plants, along with all other Japanese NPPs were shut down and have remained so to date. In November 2014 the governor of Kagoshima gave the Prefecture's approval for restarting both reactors. However, the NRA has still to complete its safety review of the nuclear safety case and emergency response procedures, following which it has to complete pre-start-up inspections, all of which is likely to delay the readiness of both NPPs for restart until February-March of 2015 or later.

NRA REGULATORY FRAMEWORK – APPLICATION TO SENDAI NPP

A) INTRODUCTION AND ABANDONMENT OF THE *'DESIGN-BASIS'*

As previously discussed (**PART I**), the NRA introduced a new regulatory regime for commercial nuclear power reactors (NPPs). The principled approach incorporated into this new regime is set out by the NRA in its *'Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors'* and its attachment *'New Regulatory Requirements for Light-Water Nuclear Plants – Outline'.*[8]

In January 2013 the NRA pledged to:[4]

> *". . . In particular, safety standards for design basis (DB) should be re-established, taking into careful consideration the lessons of Fukushima.*
>
> *. . . to improve the safety margin of equipment for DB requirement against natural phenomena . . . "*

with undertaking being further enunciated by the NRA in the '*Outline of New Regulatory Requirements (Design Basis)'* of April 2013 that includes the requirement to establish a *design basis* for *natural phenomena* other than earthquakes, where *'anticipated natural phenomena'* include, amongst other things *'volcanic effects'*. [5]

In other words, the substance of NRA's new regulatory approach was then, in 2013, that each reasonably anticipated natural event, ie a volcanic eruption, required identification of the *design basis* parameters which are to be derived from a hazard assessment of the anticipated volcanic event. Moreover, at this stage of the development of the *New Regulatory Requirements* (April, 2013), the NRA clearly aimed at underpinning the NPP licensing with a framework of *'design-basis'* conditions or cases that catered for, amongst other natural phenomena, the effects of volcanic activity.

In July 2013 the NRA introduced the series of newly developed and/or strengthened safety guides (**APPENDIX II)** and, of specific interest here, *'(1) Volcano Evaluation Guide'* which in application is entitled 原子力発電所の火山影響評価ガイド (*The Assessment Guide of Volcanic Effects to Nuclear Power Plant – Draft*, hereafter referred to as the *Volcano Assessment Guide*).[7] This *Volcano Assessment Guide* does not itself refer to establishing the parameters for the appropriate *'design-basis'* cases, although it refers directly to the IAEA volcanic site assessment[27] which endorses strongly the *'design-basis'* approach.

B) SENDAI NPP COMPLIANCE WITH THE NRA VOLCANO ASSESSMENT GUIDE

TABLE A of **APPENDIX IV** sets out in general terms (Col 4) those aspects of the Sendai NPPs that are likely to have to comply with the NRA's *New Regulatory Requirements*[8] (Cols 2 and 3) and if and how these are specified in the *Volcano Assessment Guide*[7] (Col 5) – all of these comparisons are made on the basis of volcanic events and particularly relating to tephra ash fall. From **TABLE A**, obviously, the requirement to establish a *'design-basis'* case for volcanic effects no longer exists. It is not clear why the NRA's previously identified *'design basis'* approach has been abandoned in the detailed framing of the new regulations, particularly in the *Volcano Assessment Guide.*[7]

In September 2014 the NRA provided a summary[55] of the Kyushu Electric application to restart Sendai NPPs in account of the changes and modifications undertaken during the period of enforced shut down (essentially, the application to restart the NPPs in compliance with the *New Regulatory Requirements*). This document, of uncertain application in Law, includes section III-4.2.2[47] specifically addressing *'the design policy against the effects of volcanic activity'* and, it is assumed, compliance with the *Volcano Assessment Guide.*[7]

Section III-4.2.2 addresses a range of volcanic effects beyond the tephra ash fall of specific interest in this Review. However, it is worthwhile précising the screening processes and remedial measures as these apply to tephra fallout defined within the nine specific Stages identified by the NRA, these generally correspond to the NRA earlier draft flow chart (Figure 1) of **APPENDIX I** and the IAEA so-called *Methodological Approach* of **DIAGRAM 1**.[27]

Referring to **DIAGRAM 1**, the first four NRA Stages correspond to the IAEA *1st Initial Assessment*, the *2nd Characterisation of Sources of Volcanic Activity,* and the *3rd Hazard Screening by Type and Distance from the NPP*:-

STAGE 1] **Characterisation of Volcanoes that May Affect the Sendai NPPs:** Based on an initial screening distance of 160km, as defined by the NRA, and taking into account past volcanic activity during, first, the Quaternary and then, second, the Holocene periods.

Via this relatively crude, first-stage screening filter, the NRA arrives at the number of capable volcanoes within range of the Sendai NPPs to be 14. Note, however, that the *Volcano Assessment Guide*[7] introduces further screening (smaller) distances applied to particular volcanic effects – see **CHART 1** of **APPENDIX I**.

STAGE 2] **Likelihood of Volcanic Activity during the Remaining Lifetime of the Sendai NPPs:** The task reported here involved evaluation of the potential activity of the volcanoes identified by 1] above. A VEI 7 magnitude volcanic event is adopted as a yardstick on the basis, it is assumed, that it will result in a severity of damage to the NPP reactor primary circuit and nuclear island containment sufficient for a catastrophic radioactive release and intolerable radiological consequences. On the other hand, a VEI 6 event is considered not to result in any impact and radiological outcome at the Sendai NPPs.

STAGE 3] **Monitoring of Volcanic Activity:** The monitoring programme is aimed at assessing the possibility of a VEI 7 event unfurling to gain sufficient advance notice to enable Kyushu Electric to cease reactor criticality and to transfer the reactor core and spent fuel from the Sendai

There are a number of uncertainties not resolved by the 2nd and 3rd stages of the NRA's assessment:

a) First, there is the artificial cut-off threshold that an event below VEI 7 will have no impact and radiological outcome at the NPP. Indeed, not demonstrated is a clear relationship between the evidence of past (unobserved) volcanic events and the VEI rating but, importantly, the screening assumes that the dominant volcanic effect (ie pyroclastic surge) is

47 Section III-4.2.2 – about 8 pages of Japanese kanji writing characters.

the only effect that can, either directly or indirectly (or both) at VEI 7 magnitude result in damage and malfunction at the NPP site, whereas it is assumed without any justification that a VEI 6 (and less) event would not result in any radiological impact from the Sendai NPPs.

TABLES 1 and **2** show the comparative levels of volcanic effects, including tephra ash fall, related to distance from the NPP over the VEI scale. Albeit crudely, the comparison indicates that events within the range of VEI 3 to 6[48] could intrude into and impact upon the Sendai NPPs and surrounding land and sea areas, certainly of sufficient magnitude to introduce difficulties in maintaining the plants operational and, even if shut down, stabilize and cool the reactor plant and spent fuel ponds.

b) There is great reliance upon the recently published work of Druitt, et al[56] in the ability and reliability to forecast a forthcoming eruption within months and/or years of the event essentially by monitoring the mixing of different silicic in the magma reservoir.[49] Druitt's work has been widely discussed and debated in Japan, with it featuring much in the discussions of the 1st Meeting of the NRA *Volcanic Monitoring Team*.[57]

Adopting the (Druitt driven) strategy of monitoring capable volcanoes displaces the advanced probabilistic approach recently demonstrated for the (never fuelled and commissioned) Bataan NPP.[58] This analysis yielded probabilities (for Mount Natib, Philippines) of ~1.E-4 to 2.E-4 per annum at 95% confidence, being sufficient to consider future VEI 6 eruptions to be credible events.

STAGE 4] **Impact Assessment of Volcanic Events:** Adverse volcanic effects, other than tephra ash fall, are screened out by distance of the NPP from the nominated volcano Mount Sakurajima (about 40km distance from the Sendai NPPs) and the Satsuma eruption magnitude of BP[50] 12,800a with about 11km^3 ejecta volume. This gave rise to a tephra fall volume that, according to the NRA, resulted in a past tephra deposited layer of 12.5cm or less thickness at 1.5g/cm^3 specific density when water saturated.

On ejecta volume alone, the nominated Sakurajima Satsuma eruption is slightly over VEI 5 (according to **TABLE 1**). The tephra dispersion and deposition layer record is shown by **FIGURE 17** with the present day location of the Sendai NPPs shown 40km to the north-west of the Satsma vent. The west-east deposition

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48 Of course, VEI 7 and 8 events are so severe effects, being continental and global in scale, that the radiological impact of one or more NPP failures might be considered relatively insignificant compared to the widescale environmental and human loss likely to be encountered.

49 The Druitt, et al 2012 work[56] examines the pre-eruptive processes occurring in the magma reservoir of a past (17th C) eruption of the Santorini Volcano in Greece. It evaluates the timing for changes in silicic crystals in the magma reservoir of a volcano perched on the edge of a caldera-forming eruption. For the Santorini volcano a recharge of and increase in volume (by at least a few km^3) of the magma reservoir with a silicic magma is shown to have occurred rapidly (at >0.05km^3/y compared to typically ~0.01km^3/y) during the relatively short and transient volcanic timescale of about 100 years prior to eruption following an 18,000 year gestation period since the previous major eruption. However, the authors of this innovative work acknowledge that it is based on a limited study of a single volcano; that the high magma reservoir recharge rate of 40 to 60km^3 requires a low viscosity melt and very efficient mixing at a high convective Reynolds N^o; and, amongst other things, that the addition of a few km^3 of magma into the reservoir would require a significant total uplift of tens of meters, at an average rate of ~1m/y over 100 years, compared to observed rates of sustained uplift of 0.15 to 0.2m/y (Iwa Jima caldera), so the absence of such significant caldera uplift means that the accommodation of the reservoir growth has to be by an equally rapid rate of subsidence or downsagging, which is not readily detectable.

50 BP – '*Before Present* year' expressed in years.

pattern (shown - - - in contours of cm thickness) suggests north-easterly prevailing wind direction at the time of the eruption and airborne dispersion.

Crucial to understanding the tephra fall dispersion and deposition patterns and, hence, the tephra fallout the Sendai NPPs, is knowledge of the plume height and the atmospheric conditions, particularly wind direction and atmospheric stability, prevailing at the time. Since, obviously, there is no contemporary record of the BP 12,800a Satsuma event then its outcome cannot be compared in absolute terms to a future volcanic event – relatively small changes in these parameters, and/or with the VEI severity inching up towards VEI 6, could result in substantial increase in the rate and total amount of tephra deposition at the Sendai NPPs.

For example, if a future equivalent VEI 5-6 event occurred when the prevailing wind was from the south-easterly quarter then the Sendai NPPs could be inundated with the equivalent of 25 to 35cm tephra layer as shown simply by realigning (+90°) the deposition contours of **FIGURE 17**. However, as previously noted, referring to the historical record rarely provides information on the rate of tephra deposition and layer thickness (see page 11), knowledge that is vital if adequate resources are to be allocated for managing the ash.

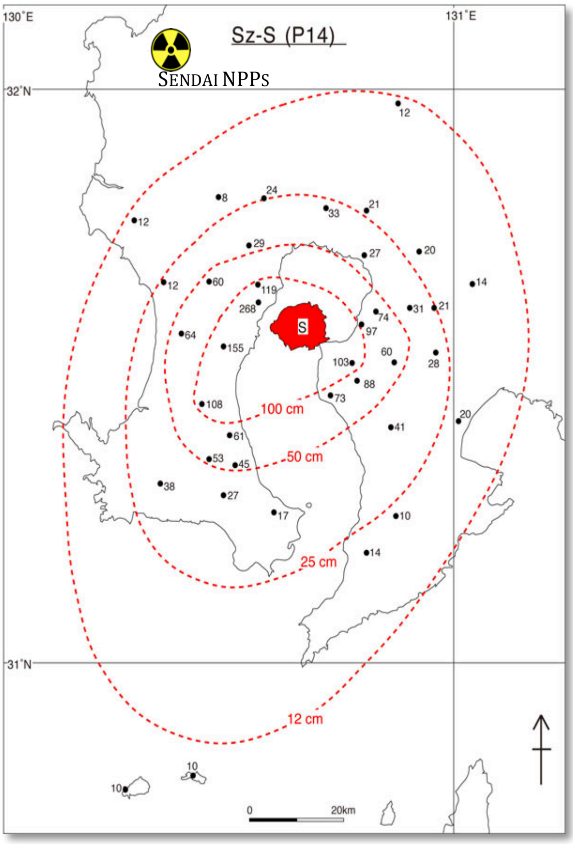


FIGURE 17 MOUNT SAKURAJIMA SATSUMA ERUPTION OF BP 12,800 – GJS – COMPACTED LAYER RECORD cm

The remaining NRA Stages collectively correspond to the final IAEA methodology, being to *Evaluate Specific Hazards at NPP Site*:-

STAGE 5] **Protection of Equipment Against Volcanic Effects:** This NRA specified stage requires Kyushu Electric to assess and, where appropriate, modify safety equipment under the existing CLASS 1, 2 and 3 safety ranking system.

STAGE 6] **Countering Direct and Indirect Impact from Volcanic Effects:** In application of 5] above, Kyushu Electric is required to identify both *direct* (ie blocked filters, etc) and *indirect* (ie vehicle access to NPP site, LOOP, etc) that will influence safety performance of the NPPs during and in the aftermath of a volcanic eruption.

STAGE 7] **Determine and Set the Design Load:** Relating to deposited layers of tephra, this includes for static, superimposed loading on roofs, tanks and other exposed structures, and similarly, on components that are exposed to ash fall and/or intake. Kyushu Electric summarises the design loads and other impacts in Section 4-2-4 of its 0035-13/14 submissions to NRA:[59]

TABLE 4 4-2-4. RESULT OF THE ASSESSMENT OF DIRECT IMPACTS (unofficial translation)

Assessed Target Facilities	Result	Note
Reactor building, Reactor auxiliary building, Fuel handling building, Diesel building, Building of main steam pipe rooms	Allowable load of sedimentation to those buildings is more than approx. 4000 N/m^2 although load of pyroclastic fall deposit's sedimentation is 3,000 N/m^2, therefore, pyroclastic fall deposit doesn't affect their safety. Also, the chemical corrosion caused by pyroclastic fall deposit will not give any immediate impact to their functions since the buildings' exteriors are coated by paint.	1
Condensate tank, Refueling water storage tank	The result of stress evaluation of pyroclastic fall deposit tells; their body and roofs are sound and they aren't affected. Also, the chemical corrosion caused by pyroclastic fall deposit will not give any immediate impact to their functions since the buildings' exteriors are coated by paint.	2
Seawater pump	The function will not be affected by pyroclastic fall deposit because even a motor frame (which is considered to have some difficulties when pyroclastic fall deposit accumulates) has enough safety margin to endure occurred stress. Also, the chemical corrosion caused by pyroclastic fall deposit will not give any immediate impact to their functions (of outside, inside, and water system) as the buildings' exteriors are coated by paint and anti-fouling paint. Pyroclastic fall deposit will not adhere to pump shaft as the relief groove for foreign substances is set on the pump bearing. Electric system and instrumentation control system will not have any mechanical and chemical influence and its cooling tube will not be blocked up, because the seawater pump motor's cooling system is a totally enclosed fan-cooled type and it shuts out pyroclastic fall deposit.	3
Main steam relief valve (Silencer)	A silencer is installed on the air release mechanism, and the structure of the silencer and pipe arrangement are formed in such a way as to make pyroclastic fall deposit difficult to enter the pipe directly. If the deposit enters directly to the pipe and blocks it, the function will not be affected because the blow-off power of the main steam relief valve is bigger than the load of the deposit.	4
Main steam safety valve (Exhaust pipe)	Exhaust steam pipe(s) is laid out / is structured to make pyroclastic fall deposit difficult to enter into the pipe directly. If the deposit enters directly to the pipe and blocks it, the function will not be affected because the blow-off power of the main steam safety valve is bigger than the load of the deposit.	5
Auxiliary feed-water pump for turbines	Steam/air discharge-pipe(s) of the auxiliary feed-water pump for turbines are structured to make pyroclastic fall deposit difficult to get enter the pipe. Therefore, its function will not be affected.	6
Emergency diesel power generator	Pyroclastic fall deposit cannot enter because of the flow of incoming air of the engine. Also layered filters will catch the deposit, and the deposit (ash) will be easy to get fractured because of the low elevation. Therefore, its function will not be affected.	7
Ventilation and air-conditioning facility	A flat filter is installed at the air-intake of the ventilation and air-conditioning facility, and the removal efficiency of this filter is over 85% (range of the median diameter is 6.6 to 8.6 µm). The aeration facility will not be affected much by the pyroclastic fall deposit as the filter removes most of the deposit. Regarding the air-conditioning system of central control room, the habitability of the room is maintained by closing the air-intake damper and operation separated from outside air. Also, ash on filters can be removed since it is accessible enough from the turbine building and they can be cleaned / replaced easily, as necessary.	8
Exhaust stacks of auxiliary building and containment	The exhaust velocity of the exhaust stack of the auxiliary building is more than the descent velocity of pyroclastic fall deposit, therefore, stacks will not be blocked up by the deposit. Also, corrosion will not give immediate impact to its function since the exteriors are coated by paint.	9
Water intake facility	The grain diameter of pyroclastic fall deposit is very small and it doesn't block the dust removal device.	10
Seawater strainer (including downstream equipment)	Pyroclastic fall deposit will not block the strainer because its grain diameter is smaller than holes of mesh (net) of the strainer. The deposit which passes through the strainer's mesh (net) will not block / give any influence to the equipment of downstream (coolers and refrigerators). Also, corrosion will not give immediate impact to its function since the exteriors are coated by paint.	10
Tanker lorry	There is plenty time (about 24 hours) to start transferring fuel. Also, corrosion will not give immediate impact to its function as the exteriors are coated by paint. It is usable by cleaning its air filter as necessary.	10

The superimposed static loading of the tephra fall on various built structures (flat roofed buildings and tank tops) is also given in the 0035-13/14 submissions:[59]

TABLE 5 INDIVIDUAL ASSESSMENT 1 - REACTOR BUILDING, AUXILIARY BUILDING, FUEL HANDING BUILDING, DIESEL BUILDING, BUILDING OF MAIN STEAM PIPE ROOMS (unofficial translation)

TARGET FACILITIES		BUILDING ASSESSED *2	ALLOWABLE TEPHRA LOAD (N/m²) *3	IMPOSED TEPHRA LOAD - N/m² FOR 0.15CM THICK TEPHRA LAYER	MARGIN
Reactor building	R1	Roof slab *4	6200	3000	2.07
	R2	Roof slab *4	6200		2.07
Reactor auxiliary building	R1	Roof slab	8100		2.70
	R2	Roof slab	8100		2.70
Fuel handling building	R1	Roof slab	5100		1.70
	R2	Roof slab	4400		1.47
Diesel building	R1	Roof slab	9800		3.27
	R2	Roof slab	8100		2.70
Main steam pipe rooms	R1	Roof slab	9800		3.27
	R2	Roof slab	8100		2.70

[Kyushu Electric table notes]

*1 The area Sendai NPP is located does not need to consider the combination of a load of snowfall and earthquake force, based on *Order for Enforcement of the Building Standard Act.* Sedimentation of pyroclastic fall deposit is less frequent than accumulation of snow, therefore, it is not considered with earthquake force. However, the work for removing pyroclastic fall deposit is carried out promptly to decrease the load of sedimentation.

*2 Slab was selected for the assessment as the part most subjected to external forces and has the smallest live load (its own weight).

*3 The load of pyroclastic fall deposit's sedimentation was assessed as a short-term load (allowable load of sedimentation is the reminder after the long-term load has been deducted in the short-term allowance stress design).

*4 The middle part of the dome will not get concentrated accumulation of ash when the ash slides down from the top of the roof, because its surface is even (no levels).

STAGE 8] **Procedures for Controlling/Mitigating the Direct Effects of Tephra:** These measures for managing and clearing the tephra deposits (and filter blockage, etc) are given by Kyushu Electric in its response to NRA's interrogatories of March 2014.

For tephra layer clearance Kyushu Electric provide analysis for only the nuclear island buildings and external tanks (condensate and refueling water storage) flat roof area totaling about 18,400m², thereby excluding the large areas of flat roofs of the common turbine building, the diesel generators, general administration buildings and internal site and off-site electricity substations – these additional areas of flat roofing and open areas account for approximately 10,000m² that would, as prioritised in account of its load capacity and function, also require labour.

Kyushu Electric's tephra layer clearance analysis is limited to a maximum layer of 15cm thickness. According to Kyushu Electric's analysis, a team of two labourers working 6 hours (with 2 hours rest) will require a prodigious 263 days so, it follows that, 15 teams would clear the ash over 18 days, or 30 teams each working one of two alternate shifts per day would clear the ash in 9 days or thereabouts. The total days spent clearing the ash if the additional 10,000m² of buildings etc., not included in the Kyushu Electric analysis are taken into account, require approximately 405, 28 and 14 days respectively.

These approximate clearance times do not account for additional labour and delays by gaining access roads and pathways to certain areas, clearing winded drifted areas of tephra, freeing the electricity distribution and substations yards, seawater intake screens, etc., nor, indeed, for hiring, bringing onto the NPP site the small army of extra labour required for these tasks, thereafter organizing and equipping them for work in a relatively dangerous and hostile environment (ie up to sixty or more labourers and their supervisors).

In fact, Kyushu Electric seem somewhat optimistic with is assessment in its reconciliation of the tephra ash clearance task. For example the tephra removal work method does not seem to account for the viscous 'stickiness' of the rain sodden tephra, thus requiring greater effort to extract it from the accumulated layer, deposit it in the wheelbarrow and then extract it from the same; that the working and working surfaces will be slippery, thus slowing transit times; and if the ash fall is continuing then the working light will be poor, further slowing the work. In account of these factors contributing to further hindrance of the clearance, using published UK labour rates data[60] the 30 two-man teams require around 29 compared to the 14 days of the Kyushu Electric analysis.

Another presumption of the Kyushu Electric analysis is that the total tephra thickness will be limited to 15cm compared to the historic BP 12,800a Satsuma record of up to about 30cm tephra layer thickness (see reorientation of **FIGURE 17**). If a tephra layer thickness of 30cm was allowed to accumulate with no clearance, the two most vulnerable roofs of the R1 and R2 spent fuel buildings would exceed their respective design loads by factors of x1.18 (design margin 0.85) and x1.4 (0.73) respectively.

Finally on the projected Kyushu Electric analysis, the assumption throughout is that the tephra fallout has ceased. If, however, the tephra fallout continues unabated once that the deposited tephra layer thicknesses at the various flat roof and tank localities nears to or reaches its allowable load or structure limit (see Col 4 **TABLE 5**), then tephra removal will have to be carried out commensurate with the deposition rate.

For example, to keep abreast of the total roof area of ~28,000m^2 at the reported 1.3cm/hr ash fall rate in the 50km distal locality the 1980 Mount St Helens event, a minimum of around 7 two-man teams would have to be continuously deployed (hour for hour of the tephra ash fall). In reality, to provide adequate ash clearance cover across the entire site, because the separate roof areas are separate and dispersed around the NPP site, two groups of 7 teams might be required for each of three shifts to cover each 24 hours, the total labour result at hand could be as high as 42 teams or around 80 to 90 individual labourers.

Under continuing tephra fallout and, particularly, if conditions are wet, clearing the sticky and heavy tephra with slippery underfoot conditions in poor visibility and at roof height could be both arduous and dangerous for the personnel involved.

STAGE 9] **Response to Loss of External Power Supplies (LOOP) for 7 Days:** These measures involve the logistics of providing and maintaining physical inputs to the NPP to ensure uninterrupted and sufficient electricity supplies, via off-site mobile emergency generator sets and restoration of on-site emergency diesel generator supplies, to enable reactor core and spent fuel pond cooling to be maintained, together with essential safety systems.

Having adequate measures in place to maintain the tephra ash fall accumulation at ground level and on critical (structural) surface to manageable levels, together with keeping machinery and filters free of ash, is an essential prerequisite to stave off a total station blackout (SBO) during LOOP conditions.

From **TABLE 2** and with a degree of deduction, it is reasonable to construct the principal tephra fall *design-basis* parameters for the Sendai NPPs:

TABLE 6 DESIGN-BASIS PARAMETERS FOR SENDAI NPPS – TEPHRA FALL ONLY

				NPP DESIGN BASIS PARAMETERS		
REGULATOR NPP	**LOCATION**	**FOREWARNING**	**CLOUD HEIGHT**	**TEPHRA FALL DURATION**	**TEPHRA FALL RATE**	**LOOP DURATION**
NRA Japan Sendai	40km West Mount Sakurajima	Not Specified Assumes Druitt forewarning 100 years, decades, months	Not Specified	Not Specified	Fall Rate not specified layer compacted thickness preset at 12 to 15cm	7 days onset timing not given
NRC USA Columbia	220km East Mount St Helens 165km E Mount Adams	2 hrs	>12,000m	20 hours	>0.53cm/hr total fall layer thickness 10.60cm – ash drop period 20 hours	from 2 hrs following volcano eruption

The final row of **TABLE 6** shows the principal tephra fall *design-basis* parameters for the US Columbia NPP. The tephra hazard identified and adopted as a *design-basis* for the Columbia NPP is assumed to have a final layer deposition fall rate of 0.53cm/hr occurring at a distance of (for an eruption at Mount St Helens) 220km. Since the general rule is that the deposition layer thickness, and hence the fall rate, would be higher at localities nearer to the volcanic vent, the equivalent fall rate at 40km – the distance between Sendai NPP and Sakurajima – would be significantly higher.

For the Columbia NPP the *Abnormal Condition Procedure ABN-ASH* triggers a managed shut down of the reactor plant and the assumption is that NPP must be readied for loss of off site power or LOOP. In this state of readiness, the emergency diesel generators at the Columbia NPP would be in operation ready to pick-up the on-site electrical power demand should off-site electricity supplies fail. As previously discussed, at Columbia (220km from the St Helens vent) the each diesel generator aspiration intake filter would clog and require changing every 2.3 hours and, similarly, the generator room air intake filters would have to be changed every 3.6 hours.

In the Kyushu Electric Sendai NPP assessment under **STAGE 7** above, there is no provision for changing the air filters for the ventilation of the emergency generator enclosures, although the aspiration filters to the generator engines require replacement, according to Kyushu Electric, every 26.5 hours runtime (compared to 2.3 hours for Columbia) with the filter change operation occupying 8 personnel for about 2 hours, with each operational generator equipped with 2 switchover filters.

However, the basis of this filter change runtime period assessment[61] assumes a local atmospheric concentration of 3,241μg/m^3 (taken from the Iceland Eyjafjallajökul eruption of 2010) but which bears no relationship to the fall rate assumed to yield the 12 to 15cm tephra deposited layer thickness, nor is there any account of the tephra particle size airborne at the Sendai NPP locality. Also, there is no account of a higher tephra fall rate if, for example, the historic geologic record (FIGURE 17) had, by chance, occurred with a easterly wind direction and a considerably higher tephra deposition layer and correspondingly higher airborne concentration rates (ie more frequent filter changes).

C) COMMON SENSE COMPLIANCE OF THE NRA REGULATORY FRAMEWORK

TABLE 7 summarises the common-sense parameters (2nd column) in established use by the US NRC[35] and, in more general terms, as expressed and recommended for NPP site evaluation by the IAEA[27] – for this Review emphasis has been given to tephra fall over other volcanic effects.

TABLE 7 SUMMARY OF VOLCANIC-HAZARD ASSESSMENT AT A NPP SITE (FOR TEPHRA FALL ONLY)

		INCLUDED IN	
ITEM	DESIGN-BASIS ASSESSMENT PARAMETER [51]	NRA SUMMARY[55] OF SENDAI VOLCANIC ASSESSMENT[7]	VOLCANO ASSESSMENT GUIDE[7]
1	Eruptive histories of volcanoes whose explosive eruptions could result in tephra fall at site.	✓ III-4.2.2 – 1 (1)	✓ S2, 3.1, 3.2, 3.3
2	Frequency of explosive eruptions of volcanoes identified in Item 1) during past 2,000, 15,000, and 100,000 yr.	✓ III-4.2.2 – 1 (2) also covers Quaternary	✓ S3.1 S3.2 S3.3(1), (2)
3	Stratigraphic record of tephra fall at site and in region within 50 km of site.	✓ III-4.2.2 – 4 (1)	✓ S6 S6.1(1a) direct impact S6.1(1b) indirect impact
4	Probable range in uncompacted thickness of tephra at site based on distance versus thickness plots of model tephra layers of various volumes.	✓ III-4.2.2 – 4 (3) data assumed solely from past event BP 12,800a – Satsuma- single thickness only	✗ not a specified requirement
5	Annual probability at site of tephra fall of 1 cm, 10 cm, and 1 m.	✗ data taken from single past event BP 12,800a - Satsuma	✗ not a specified requirement
6	Maximum expectable thickness of tephra fall at site.	✓ III-4.2.2 – 4 (1) 12 to 15cm saturated	✗ S6 - Chart 1 relies upon past tephra deposits found around NPP site
7	Upper-level wind-direction frequencies and velocities at site.	✗	✗ not a specified requirement
8	Range at site of possible grain size of tephra from volcanoes in Item 1).	✗	✗ not a specified requirement
9	Range in densities of tephra considering composition, grain size, and moisture content.	✓ III-4.2.2 – 4 (3) very limited	✗ not a specified requirement
10	Probable tephra loads on structures using Items 4),	✓ III-4.2.2 – 6 (1)	✓ S6.1(2)

51 Column 2 from Table 6.4.[35]

	6), 8), and 9), and the effects of drifting of tephra by wind.	– 7 very limited, no drifting, assumes roofs manually cleared	direct impact
11	Range in rates of tephra accumulation, duration of tephra falls, and duration of darkness and poor visibility caused by tephra.	✗	✓ S6.1(2) direct impact
12	Range in arrival time at site of tephra erupted from various volcanoes.	✗	✗ not a specified requirement
13	Effects of atmospheric shock waves caused by a volcanic explosion.	✗	✓ S6.10(1) not quantified
14	Expectable patterns of post depositional erosion and redeposition of tephra by wind and water, and other processes at site.	✗	✗ not a specified requirement

The 3rd column of **TABLE 7** lists the salient points of the NRA's summary[55] of the Kyushu Electric submission in accord with the *Volcanic Assessment Guide*;[7] the 4th column lists the main features (requirements) of the *Volcanic Assessment Guide*;[7] and the 2nd column is the common-sense prerequisites established by Hoblitt, et al[35] that, essentialy, now provide the basis of the US NRC approach to volcanic hazard and risk assessment and the siting of NPPs.

Like the general case presented by **TABLE A** of **APPENDIX IV**, it is quite clear from **TABLE 7** that, in application to the Sendai NPPs, the new (June 2013) *Volcano Assessment Guide*[7] has not achieved the *design-basis* objective. Essentially, this is because, for the response and mitigation measures, the assessment is framed deterministically and drawn solely from a single, past volcano incident at BP 12,800a.

Further comparison of the *Volcanic Assessment Guide* with the IAEA SSG-21 methodology for NPP site assessment is available in the form of an Opinion.[62]

Volcanic hazards arise from phenomena that have broad ranges, scales and magnitudes – Both determinist and probabilistic approaches may be, and are, used to assess volcanic hazards and risks. Simply stated, deterministic methods use thresholds to screen specific phenomena from further consideration and, conversely, probabilistic methods deploy probability functions to estimate the likelihood of specific volcanic phenomena (and other NPP design and site factors that may contribute to a radioactive release).[63] The NRA adopts deterministic and some might consider arbitrary values (eg 160km and other cut-off distances of **CHART 1** of **APPENDIX I**) to screen out volcanic activity and effects.

Although a deterministic approach, like that used for the majority of the Sendai NPP evaluation of **TABLE 7**, might provide a transparent basis for decision-making, screening criteria are often difficult to develop because such depend on the surviving geologic evidence which may be a poor physical record of a limited number of past events. Large uncertainties in the number and character of past events can focus a deterministic approach to use extreme events as the basis for decision–making. However, a probabilistic approach can readily incorporate uncertainties that arise from, for example, an incomplete geological record, take account of a range of natural variability, and incorporate uncertainties in the knowledge of complex natural events. Decisions on site suitability, together with determination of the design basis and identification of any equipment and procedural amendments necessary, are derived from the analysis of these probability distributions.[64][27]

It follows that once the initial stages of assessment have identified that volcanic hazards at the NPP site are credible external events, then the corresponding *design-basis* (or *design-bases*) should be derived for those phenomena that can occur at the NPP site and that can affect the safe operation or shut down state of the NPP. Once established, the probabilistic based *design-basis* case enables a better understanding of and readiness for *beyond-design-basis* events.

In existing nuclear installations, such as the Sendai NPPs, a change of or addition to the original design bases, or a change in the regulatory requirements regarding the consideration of volcanic hazards, may result in a significant impact on original design features and, consequently, to important modifications to equipment and operational procedures. Obviously, such modifications to satisfy a volcanic effect *design-basis* should not be at the detriment to other established safety features and aspects of the NPP.

The Kyushu Electric submission to the NRA, as summarized by the NRA,[55] reveals that this first attempt by the new nuclear safety regulator to introduce a systemised and comprehensive volcanic effect NPP site evaluation may not have been entirely successful.

APPENDIX I

LISTING
OF

THE ASSESSMENT GUIDE OF VOLCANIC EFFECTS TO NUCLEAR POWER PLANT (DRAFT) 2013, JUNE 3

(UNOFFICIAL TRANSLATION FROM THE ORIGINAL JAPANESE LANGUAGE VERSION – TRANSLATOR'S ADDITONAL NOTES AND EXPLANATIONS SHOW THUS AND SECTIONS NOT TRANSLATED IN THE ENGLISH VERSION ARE HIGHLIGHTED THUS AND TEXT TRANSLATED BY SOFTWARE ONLY IS HIGHLIGHT THUS BUT THIS TEXT SHOULD NOT BE RELIED UPON)

Doc. 0023_05

Reference material 1

THE ASSESSMENT GUIDE OF VOLCANIC EFFECTS TO THE NUCLEAR POWER PLANT (DRAFT) 2013. JUNE 3 (REVISED DATE)

< Contents >

THE ASSESSMENT GUIDE OF VOLCANIC EFFECTS TO THE NUCLEAR POWER PLANT (DRAFT) 2013. JUNE 3 (REVISED DATE)

<Main Text>

1. **General provisions** (p.1 - 2)

To properly evaluate the volcano effect on nuclear power plants, fire may affect the nuclear power plant Mountain of extraction, individual evaluation related to volcanic activity of the extract volcano, obtained affect the nuclear power plant That it is a method for the extraction and its impact assessment of volcanic events and those compiled a confirmation matters.

1.1) General background

The new regulatory standards established by the Nuclear Regulatory Commission, and design considerations for natural phenomena other than earthquake As, constructs with a "safety feature, systems and components, earthquake, other than the tsunami and seismic phenomena accompanying That the assumed natural phenomena are to a design without compromising the safety of the nuclear reactor facility. Construct with a particularly high safety feature of importance, systems and equipment, of the natural phenomena that are expected appropriate combination if an accident loads during *design basis* accident when it is considered the most severe and natural forces It is designed in consideration of the case it was Align. "The are sought, it is expected based on the natural environment of the site As one of that natural phenomena, and cites the influence of the volcano The impact assessment of the volcano, recently in the evaluation found in safety review of spent fuel interim storage facility Track record Ri nitrous, Japan Electrical Association in 2009 is "Nuclear power plants volcanic impact assessment technology finger needle" (JEAG4625-2009) is enacted, IAEA Safety Standards is in 2012 "Volcanic Hazards in Site Evaluation for Nuclear Installations "(No. SSG-21) were formulated. In recent years, volcanology basic From description science, observation and numerical value of the complex volcanic process of volcanic system was previously impossible And has been developed into a quantitative science relies on the use of the model, based on these findings, and nuclear power In order to properly evaluate the volcanic impact on the place, you have created this evaluation guide.

This evaluation guide, this compromising the safety of the reactor facility due to the impact of volcanic seeking a new regulatory standard It is intended to be used when performing an evaluation of that it is designed to not bet.

Volcanic activity is assumed during the operation period of the nuclear power plant, design corresponding non-volcanic events by it If the elephant can not be evaluated and is small enough potential to affect the nuclear power plant, nuclear Substation location is unsuitable.

1.2) Coverage

This evaluation guide is applicable to nuclear facilities in power generation for nuclear power facilities.

1-1-3. Related laws and regulations

This guide uses those documents below as a reference:

(1) Regulations about the standard of site, structure and equipment, of a power reactor and its attached facilities (Tentative title)

(2) Opinions for 'Natural environment' on the safety assessment of interim storage facility for the spent nuclear fuel (Approved by Nuclear Safety Commission, October 27, 2008)

(3) 'Engineering guidelines for volcanic effect assessment of nuclear power plant' by Japan Electric Association (JEAG-4624-2009)

(4) IAEA Safety Standards "Volcanic Hazards in Site Evaluation for Nuclear Installations" (Nº SSG-21, 2012)

1.4) Definition of terms

Definition of the term in this evaluation guide and description are as follows.

(1) Volcano

Volcano, a terrain or structures with a characteristic morphology formed by eruption. Usually, although the terrain is convex topography increases, as in the caldera is caused by precipitation, depression - in some cases of depression-shaped.

(2) Volcanic Activity

Volcanic activity, magma underground is until cooled and solidified to rise to the surface or near the In a variety of action to cause between, and so forth intrusion, eruption, hydrothermal activity volcanic earthquakes That.

(3) **Volcano Event**

Which could cause a volcanic disaster, volcano every event or series of related to phenomenon. Volcanic events may be included in the eruption, usually non-eruptions, such as landslides occurring in volcanic I also included due.

(4) **Operation Period of Nuclear Power Plant**

The operation period of nuclear power plants, and be a period nuclear fuel material is present in the nuclear power plant.

(5) **Geographical Area**

Refers to the area around the nuclear power plant that volcano impact assessment is carried out. Radius from the nuclear power plant in the range of area of 160km.

(6) **Quaternary and Holocene**

One of Quaternary Geology era, the period from 2.58 million years ago to the present. Holocene is Quaternary classification - Newest are those, a period of from 10,000 1,700 years ago until now of.

(7) **Magma Chamber**

Filled with magma, reservoir of underground. The reservoir these magma is crystallized by cooling separation of minerals, or change normally of magma composition by injection and mixing of new magma break out.

(8) **Pyroclastic**

Size, shape, regardless of the composition or forming method, any species that has been ejected from volcanoes refer to those that drop in volcanic clastics of kind.

(9) **Volcanic Ash**

The destruction of the average diameter of less than 2 mm of volcanic rock caused by explosive fracture of the various processed pieces.

(10) **Pyroclastic Density Curr**ent

Volcanic gas was produced in volcanic eruption, a general term for the phenomenon that flows down the slope a mixture of pyroclastic (That is pyroclastic flow, surge and blast).

2. Procedures of the volcanic effect assessment to a nuclear power plant

The volcanic effect assessment is carried out in two stages; Site evaluation and Effect assessment (Figure1).

For the site evaluation, we pick out volcanoes that might have influence to the plant first, then assess their volcanic activities individually if there are some influential volcanoes. The assessment will check the possibility of influence of volcanic events which it is impossible to be prepared for within the plant's design during the operation of the plant (See *Commentary 1 below). If there is no major possibility of the influence, we go to the effect assessment of individual volcanic events (with the condition that we properly work on monitoring of volcanic activities and handing procedures in the event of signs of volcanic activity). On the other hand, if there is some major possibility of the influence of volcanic activity, then the site is not appropriate for having nuclear power plant. For the effect assessment, we evaluate validity (adequacy) of procedures of operation and the plant's design to handle individual volcanic event.

*Commentary 1 In the IAEA SSG-21 document, it defines that pyroclastic density flow, lava flow, debris avalanche, landslide and slope failure, opening of new volcanic vent and land deformation, are 'volcanic events which it is impossible to be prepared for within the plant's design.' This guide applies the definition as well.

3. Volcanoes that might have effect to nuclear power plant (p.6 - 7)

To geographical area of nuclear power plants, to extract the volcano was active in the Quaternary in the literature surveys.

(Commentary 2,3) For activities volcanic Quaternary, 3.1 literature survey, 3.2 topographical and geological survey and Volcanological Survey

Is carried out, volcanic activity history, to grasp the scale eruption and its effects range, and the like. Then 3.3 I evaluate the future of volcanic activity possibilities. In this case, the regional characteristics, magma of nature, etc.Ri from the characteristics and scale of volcanic activity different thing, kind of individual volcanic ejecta, distribution, topography, scale,Eruption type, eruption pattern, overall there is a need to consider the recurrence interval, etc.. It should be noted that, similar volcano it is also important to see activities.

For this chapter volcano that has been extracted as may affect the nuclear power plants, nuclear in Section 4

Individual assessment of volcanic activity during the operation period of the power plant, Chapter 5 monitoring of volcanic activity in 及

Set to be performed corresponding study when you know the signs of fine abnormal. If the volcano that may affect the nuclear power plant is not extracted, the nuclear power plant or its of the basis of the maximum accumulation amount of the observed pyroclastic around, evaluation of the effect pyroclastic 6.1 described below Worthy.

Commentary -2. For activities volcanic Quaternary, Volcanological Society of Japan, the National Institute of Advanced Industrial Science and Technology provides a database

To have 2009 conducted International Union of Geological Sciences (IUGS) is Quaternary redefined years, under also accepted JapanI it was decided that the limit is changed (changed from 1.81 million years ago to 2.58 million years). Database in accordance with this definition it is necessary to use a vinegar.

Commentary -3. Quaternary previously had volcano volcanic activity, Quaternary activity is not observed volcano already stop their activities

Is that a can be considered to, therefore, it is an object of study the volcano was active in the Quaternary.

3.1) Bibliographic survey

In the literature survey, aggregates volcano and its phenomenon of geographical area, the existing literature on ejecta, Or to take advantage of the database, it is a schematic of the Quaternary volcanoes around nuclear power plant (volcano Ejecta, volcanic center position, ejecta type, activity time, to understand the ejecta distribution, etc.), the latest On the See also knowledge, to determine the presence and distribution of volcanic sources in the geographic area. The survey results, Used as basic data for carrying out the terrain and geological investigation.

3.2) Study for geology and geography, and volcanological research

(1) **Terrain Survey**

The terrain survey, existing topographic maps, and based on interpretation and bathymetry data, and the like using aerial photographs, etc. The Hazuki, to perform the grasp of volcanic terrain. In addition, the acquisition of the latest data by aerial survey, if necessary to be carried out is also effective.

(2) **Geological Survey**

In the geological survey, by the literature survey and topographic survey, active position, scale and style and the ejection time If sufficient information is not obtained in the evaluation of the activity history etc., perform the surveys, nuclear Jet center position of volcanic ejecta of geographical area around the power plant, ejecta type, activity time, jet I gather the information necessary to evaluate such as mono (sediment) distribution. In the study, the sample of outcrop or bowling, volcanic ejecta by pit excavation, etc.

Performs sampling, analysis and dating, etc., to implement the collection and evaluation of detailed information. (Commentary -4)

(3) Volcanological Survey

In geological survey, volcanic ash, pyroclastic flows, volcanic ejecta of lava flow, etc. (sediment) was observed If was, I do volcanological investigation. For ash was confirmed around a nuclear power plant, to perform the following studies. Range of

① sediment, thickness, quantity, size and etc. layer thickness line shows the dispersion axis diagrams and equality diagram Equivalent static load of

② sediment (wet and dry) Pyroclastic flow that might have affected the nuclear power plant nearby, pyroclastic surge or volcanic

For each identifiable deposits caused by blasting, to perform the following studies.

① fixed object thickness, amount, density, spatial distribution

② or move by gravity, or liquidity, which is directed by volcanic blast Data about the topographical features that affect the direction and kinetic energy (these flow Possible movement has passed without leaving a measurable deposits some areas also reveal It is good) Lava flows, volcanic mud flow, capable of identifying each sediment caused by debris flow or debris avalanche

For performs the following investigations.

① thickness and amount of these flow phenomena is surging area, as well as the sediment

② fixed object of estimated temperature, speed, estimated value of the dynamic pressure Flow path and topographical features that affect the rate and distribution of flow from

③ source, sequence The data on the relationship between the current terrain and sediment to

Commentary -4. In the Geological Survey, Geological Survey (eg nuclear power plant seismic design technology guidelines to be conducted separately It is possible to see the results of a geological survey) to be performed based on (JEAG4601-2007).

3-3-3. Possibility of volcanic activity in the future

Based on results of the bibliographic survey and the study for geology and geography, and volcanological research (which are shown in 3.1 and 3.2), the assessment is carried out in two-stages (below) to pick out volcanoes that have a possibility of being active in the future, from Quaternary volcanoes in the geographical area.

(1) Volcanoes that have been active in the Holocene era

Check whether the volcano had any activity in Holocene or not. It is a widely-accepted theory that volcanoes which have been active in that era have possibility to be active in the future, therefore, we determine those are ones which have a possibility to be active (See *Commentary 5).

(2) Volcanoes that have not been active in Holocene

For the Volcanoes that have not been active in Holocene, the activity of much earlier period is assessed, from Quaternary volcanoes in the geographical area. The research is based on results of the bibliographic survey and the study for geology and geography, and volcanological research (which are shown in 3.1 and 3.2), using the stage diagram tells that the volcano's eruption period in the Quaternary, the scale of eruptions, and the break period (See *Commentary 6 and 7).

In the stage diagram that shows past activities of target volcanoes, some volcanoes are excluded from the individual assessment (of the Chapter 4) if volcanic activity have a pronounced tendency to be nearing an end and it is estimated there is no possible activity in the future (for example, the case that the period from the end of the last activity is longer than the longest break period in the past). Other volcanoes are included in the individual assessment (of the Chapter 4) since the possibility of volcanic activity in the future cannot be denied (See *Commentary 8).

If it is estimated that there will be no possibility of volcanic activity in the future, we evaluate effect of pyroclastic fall deposit (noted in Section 6.1 later) based on the largest amount of sediment of pyroclastic fall deposit observed in the plant and the near area.

*Commentary 5 Coordinating Committee for Prediction of Volcanic Eruptions (of Japan Meteorological Agency) defines an active volcano as 'the volcano that has erupted within about 10,000 years, and the one has fumarolic gas activity at the moment' (2003). This guide defines those volcanoes as the ones which have been active in Holocene. There are 110 active volcanoes, as at June, 2011.

*Commentary 6 In IAEA SSG-21, the assessment could be done based on relation between time and amount of volcanic system, or on petrographic trend. For example, time and amount of volcanic system sometimes tells definite tendency of weakening of volcanic activity and break period, in the Early Pleistocene or earlier period. Under such conditions, new volcanic activity is extremely unlikely to happen.

*Commentary 7 It is possible to tell that volcanic activity has ended by showing the current states of the volcano, with information gained from geochemical and geophysical research (noted in Section 4.2 later).

4. **Individual assessment for volcanic activities during operation of the plant** (p.8 - 9)

The individual evaluation related to volcanic activity in the operational period of the nuclear power plant in Chapter 3, for the volcano was evaluated that there is a future activities possibility, during the operation period of the nuclear power plant To perform the evaluation of the possibility of volcanic activity with a design correspondence is impossible volcanic events in. At this time, Ken The activities of 討 subject volcano from the point of view of scientific understanding, with past volcanic activity history, required under Flip, the 4.2 is carried out geophysical and geochemical surveys, also together evaluation situation of the current volcanic activity It is assumed that you are. Specifically, from the geophysical point of view, magma associated with consideration volcanic Size and position of the reservoir, for underground structures, etc. related to the supply system of magma, or geochemical point of view La, by analyzing the volcanic ejecta such consideration volcano, understand the activities of the volcano To.

4-4-1. Assessment for volcanic activities including some events which it is impossible to be prepared for within the plant's design

*NOTE: In the interests of a smoother translation I have changed 'Volcanic events which it is impossible to be prepared for within the plant's design' to an equivalent description of 'Volcanic events exceeding the plant's design limit' in the document.

(1) Volcanic events which it is impossible to be prepared for within the plant's design

Volcanic events exceeding the plant's design limit are: pyroclastic density flow, lava flow, debris avalanche, landslide and slope failure, opening of new volcanic vent and land deformation (out of volcanic events shown in the Chapter 6). For volcanic events which it is impossible to be prepared for within the plant's design, the volcanic events are excluded from target of the assessment if the distance between the target volcano and the nuclear power plant is longer than the distance shown in Figure.1.

(2) Assessment of possibility of volcanic activities

The geochemical and geophysical research (shown in Section 4.2) takes place as necessary depending on the result of the research in Chapter 3. Based on the result of the geochemical and geophysical research, we make a comprehensive assessment of the possibility of the target volcano's activity during operation of the plant. If the assessment says that the possibility of the target volcano's activity is small enough, a volcano, whose volcanic events exceed the plant's design limit, have reached the plant by the largest-scale eruption in the past, are picked out. Then the assessment of volcanic activity in the period of plant's operation is carried out continuously with monitoring of volcanic activity (based on procedures of the Chapter 5). If the possibility of target volcano's activity is not considered to be small enough, 'the assessment of the scale of volcanic activity and volcanic events exceeding the plant's design limit' (which shown in next (3) section) will be carried out.

(3) Assessment of volcanic activity's scale and volcanic events which it is impossible to be prepared for within the plant's design

We estimated scale of the eruption based on the research results of the target volcanoes. If it is hard to estimate the scale of the eruption from the research results, the largest scale of eruption which the target volcano had in the past is used.

Next, we assess whether how possible the volcanic events exceeding the plant's design limit reaches to the plant, in the set scale of eruptions. In the assessment, if the scale of the eruption is set based on the research of the target volcanoes, it is assessed with reference of similar volcano's span of influence by the volcanic events exceeding the plant's design limit. If a scale of the eruption is set based on the largest eruption in the past, a span of the influence is assessed with trace of the volcanic events exceeding the plant's design limit of the target volcanoes. If span of the influence is impossible to be estimated in either method, the largest recorded distance of the volcanic events exceeding the plant's design limit travelled in Japan is used as a span of the influence.

If the assessment predicts the possibility that the volcanic events exceeding the plant's design limit reaches to the plant is large, the site is inappropriate to have a nuclear power plant. If the possibility is low, the targets for monitoring are volcanoes that their volcanic events exceeding the plant's design limit are considered to have reached to the plant by largest-scale eruption in the past. Then the assessment of volcanic activity in the period of plant's operation is carried out continuously with monitoring of volcanic activity (based on procedures of the Chapter 5).

4.2) Geochemical and geophysical research

The geophysical surveys, seismic velocity structure, gravity structure, resistivity structure, seismic activity and crustal Conducted a study on change, the size and position of the magma chamber, land related to the supply system of magma I investigate under structure and the like. Commentary 8,9,10,11,12)

The geochemical survey, chemical composition analysis of volcanic gas (fumaroles), from information such as temperature, and geography I investigate the volcanic activity of the volcano that exist in regions

Commentary -8. Seismic velocity structure Spatial distribution of seismic wave velocity determined by analysis of seismic

Commentary -9. Gravitational structure Spatial distribution of the density that is obtained by gravity survey (precise gravity measurements)
Commentary -10. Resistivity structure Spatial distribution of resistivity is obtained by electromagnetic exploration
Commentary -11. Seismic activity The earthquake phenomenon in around the volcano
Commentary -12. Crustal movement Deformation phenomenon of crust due to the seek volcanic activity by GPS surveying, etc.

5-5-1. A watch list of volcanoes

The monitoring applies to volcanoes whose volcanic events exceeding the plant's design limit are considered to reach to the plant, even though the individual assessment says those volcanoes don't have much possibility of volcanic activity in the period of plant's operation. The intention of this monitoring in the period of plant's operation is to continuously check that the possibility of eruption stays low. If the result of the monitoring shows any sign of possibility of eruption, we make a required response.

Target volcanoes that are to be watched are ones with which volcanic events exceeding the plant's design limit are considered to have reached to the plant by the largest-scale eruption in the past. Observations of earthquake activity, land deformation, and volcanic gas, are points to be watched.

5.2) Points to watch

The monitoring item of volcanic activity generally include the following items.

· Observation of seismic activity (observation of volcanic earthquakes)
· Observation of crustal deformation (observed crustal movement and using the GPS, etc.)

And volcanic gas observation (observation, such as sulfur dioxide and carbon dioxide amount that is released) Seismic activity, be monitored by the appropriate method crustal movements and volcanic gas status, etc.. Monitoring business Who it is assumed that their own to implement, in the case where the public agency is monitoring the volcanic activity, and the It is also possible to use the monitoring results. (Commentary -13)

Commentary -13. Currently, 110 active volcanoes is specified by the Japan Meteorological Agency, for the observation system is formed from volcanic of these

Are. In addition, other volcanic also including we perform a planned investigation observation and by visiting the local, volcano If the increase of activity was seen, I have to strengthen the observation posture. In addition, the Japan Meteorological Agency as secretariat, Prediction of Volcanic Eruptions Liaison Committee has been established, in addition to performing a comprehensive study for the whole country of volcanic activity, volcano At the time, such as eruption abnormal, extraordinary in and held the Executive Committee and Liaison Committee, to consider the volcanic activity, required field When are doing the activities that contribute to disaster prevention by, for example, to announce a unified opinion.

5.3) Regular assessment

The monitoring results are regularly evaluated and to understand the activities of the volcano, there is no change in the situation Confirming that. (If necessary, implementing geophysical and geochemical investigation.) At that time, volcanic activity monitoring of situation result evaluation, the advice of a third party (volcano expert, etc.) Be a get policy. The operators monitoring should be performed, shutdown of the reactor, for performing unloading, etc. nuclear fuel Is a monitor, not volcanic experts only, and is composed of a nuclear and related technicians, transparent, public Flat resistant certain that you are building a mechanism to perform the evaluation of monitoring results. In addition, the monitoring results, it is Shi desirable to provide information to the public agencies or the like have.

5.4) Handling procedure in the event of signs of volcanic activity

By monitoring, be determined and the like deal policy of if you know the signs of volcanic activity.

(1) and signs of volcanic activity to be grasped in order to take corrective action, and pairs if you grasp the sign Criteria for take processing

(2) Based on the signs that have been grasped by monitoring of volcanic activity, and conduct monitoring of volcanic activity policy to carry out the deal is with reference to the activity information of the public institutions volcano

(3) as what to do if you have to understand the signs of volcanic activity, nuclear reactor stop, of appropriate nuclear fuel transportable Policy out, etc. is carried out

6. Effect assessment of volcanic events to nuclear power plant

Regarding the volcanoes assessed where the possibility of influence by volcanic events exceeding the plant's design limit to the plant's safety is low, if those volcanoes erupt, the assessment of them is carried out through the Chart 1 (for picking out the volcanic events which have a possibility to affect the plant's safety).

However, (a condition) of pyroclastic fall deposit shall be set that similar mass of pyroclastic fall deposit falls as the mass per unit area obtained from research in/around the plant, regardless of result of volcano chosen.

Also, the past documents / literatures should be checked as a reference to see the amount of pyroclastic fall deposit of Quaternary volcanism, since pyroclastic fall deposit is sometimes estimated to be lower in thickness (than in reality) because of corrosion etc. (See *Commentary 14)

The scale and characteristic features of each volcanic event are set for carrying out effect assessment. (See *Commentary 15)

The method for effect assessment of each volcanic event are stated below in this Chapter.

*Commentary 14 The literature for reference includes *'Quaternary maps of Japan'* by Japan Association for Quaternary Research.

*Commentary 15 About positional relation to the nuclear power plant: The distance stated in Chart 1 cited from Guidelines for technology of volcanic impact assessments in nuclear power plants (JEAG4625). The JEAG4625 document uses the largest recorded distance of volcanic ejecta travelled in Quaternary era in Japan, as reference for setting distance between the nuclear power plant and target volcanic events. For the case of position of source / center of eruption is not clear, the position is assumed through reference of the largest recorded distance of volcanic ejecta travelled in Quaternary era, and distribution of volcanic ejecta. For example, if the distance between the nuclear power plant and center of eruption is shorter than the figures stated on the positional relation in Chart 1, the plant might be affected by volcanic events.

6-6-1. Pyroclastic fall deposit

(1) Influence of pyroclastic fall deposit

(a) Direct impact

Pyroclastic fall deposit is the most far-reaching volcanic events which go over a widespread area. Even a tiny deposit of volcanic ash might interfere with the operation of the plant. Pyroclastic fall deposit would affect to static loading to the plant's construction, colliding of particles, blockage of water circulation system and abrasion in the system, ventilation system. Also there are mechanical and chemical influences to instrumentation control system and electric system, and pollution in the air around area of the plant.

Natural phenomenon like rainfall and snowfall might increase static loading of sediment (of volcanic ash etc.) significantly. Particles of volcanic ash include constituents that cause pollution of water supply and chemical corrosion (such as Chlorine ion, Fluorine ion, Sulphide ion).

(b) Indirect impact

As stated earlier, pyroclastic fall deposit goes over a widespread area, it affects the social infrastructure around the plant. It has to be considered that situations such as a long-term loss of off-site power caused by wide damage of power grid system, and access limitation to the plant, might occur.

(2) Effect assessment of pyroclastic fall deposit

In the effect assessment of pyroclastic fall deposit, sediment volume of pyroclastic fall deposit, sedimentation rate and period, characteristic features of volcanic ash, and influence on the characteristic feature of volcanic ash by possible weather conditions (such as rainfall), are considered. Then assessed is the influence of those to the nuclear reactor facility and equipment attached to it, also checked is whether the procedures are carried out when necessary, and required safety features are ensured. (See *Commentary 16, 17 and 18)

(3) Points to be checked

(a) Check points of the direct impact

(1) To maintain the health of system and equipment, and structure with safety features, in reaction to load of sediments of pyroclastic fall deposit.

(2) To prevent from losing functions of important safety equipment, such as water intake equipment, reactor equipment cooling seawater system, containment venting system etc., caused by blockage with pyroclastic fall deposit.

(3) To prevent from losing functions of equipment and system due to damage of emergency diesel power generator or/and the clogging of the filter of ventilating and air-conditioning system, caused by volcanic ash entering from fresh-air intake. Also, to maintain inhabitable environment in central control room.

(4) To handle removal of pyroclastic fall deposit in system, equipment, and structures of the nuclear power plant, as necessary.

(b) Check points of the indirect impact

In consideration of influence to outside of the plant (such as long-term loss of off-site power, and paralyzing traffic), it should be checked how to handle to keep safety of the reactor and the pool of spent nuclear fuel, through the use of stock of fuel and some support from outside etc.

*Commentary 16 If there is no observation of pyroclastic fall deposit in the plant and near area, amount of the sediment will be determined by following methods.

- Based on information of sediments of a pyroclastic fall deposit from similar volcano.
- Based on numerical simulation of pyroclastic fall deposit in the plant, through a function of elevation and relevant parameter. The function is derived from eruption's volume, height of eruption column, total particle size distribution, and variation in wind speed in the area, of the target volcanoes. In the numerical simulation, also relevant parameter from history of past eruptions and information of sediments of a pyroclastic fall deposit from similar volcano can be used as reference.

*Commentary 17 For rate and period of deposition, indirect impact to the plant is also assessed, based on events and simulations of similar volcano.

*Commentary 18 Characteristic features of volcanic ash are; particle size distribution and chemical features etc.

6-6-2. Pyroclastic density flow

(1) Influence of the pyroclastic density flow

(a) Direct impact

'Pyroclastic density flow' is an inclusive term of pyroclastic flow, surge and blast. It moves in high speed, and it usually has very high temperature over 300 degrees, therefore it creates serious impact to buildings on its flow path.

Also, it has far-reaching impact and its spread cannot be controlled by some landform, usually it climbs over topographical obstacles. Moreover, on occasion, it even runs across large waters. It is not possible to be prepared for this type of direct impact by pyroclastic density flow within the plant's design, therefore, it is an exclusion criterion of the location site for the plant.

(b) Indirect impact

1) As stated earlier, the impact of pyroclastic density flow / surge goes over a widespread area, it affects the social infrastructure around the plant. It has to be considered that situations such as a long-term loss of off-site power caused by wide damage of power grid system, and access limitation to the plant, might occur.

(2) Effect assessment of the pyroclastic density flow to the plant

In the assessment of pyroclastic density flow of each volcanoes which have a possibility of activity in the period of the plant's operation, we indicate influence to the plant in terms of scale and sediment volume of pyroclastic density flow of the target volcanoes, then evaluate availability of response with the plant's design. (See *Commentary 19)

(3) Points to be checked regarding indirect impacts

In consideration of influence to outside of the plant (such as long-term loss of off-site power, and paralyzing traffic), it should be checked how to handle to keep safety of the reactor and the pool of spent nuclear fuel, through the use of stock of fuel and some support from outside etc.

*Commentary 19 The IAEA SSG-21 says; the influence of pyroclastic density flow cannot be absorbed / eased by any measures (response) with the plant's design and its operation.

6.3) Lava flow

(1) **Effect of lava flow**

(a) direct impact

Lava flow is usually not destroyed or buried engineering structures in the path at a high temperature of viscous fluid That. Physical properties of lava depends on its components, the moving speed of the lava low viscosity fast moving distance Away becomes longer. In addition, terrain, dominated the reach of lava flow crater morphology and lava flow moves And the elements. Since the direct effect of such lava is impossible to design compatible, I rich exclusion criteria.

(b) indirect effects

Lava flow impact range as compared to the pyroclastic and fire 砕密 degree of flow is narrow, put the river by the lava flow It may also be necessary to take into account that there is likely to generate a flood by gas stop and snowmelt. In addition, original Affect the social infrastructure around nuclear power plants, long-term external power supply mourning due to damage of the power grid That access restrictions event to the loss and nuclear power plants can occur it is necessary to consider.

(2) **impact assessment of the nuclear power plant by the lava flow**

In the evaluation of lava flows for each volcano that activity possible during the operation period of the nuclear power plant Is, the spatial extent of the nuclear power plant and possible lava flow, crater of position, terrain, discharge rate, The viscosity of the lava flow, and the duration time of the eruption in consideration, the thickness of the reach to lava flow, temperature and potential Manner rate shows the effect of perspective from nuclear power plants, such as evaluating whether the design compatible. (Solution Theory -20)

(3) **verification matter of indirect effects**

In consideration of the impact of nuclear power generation off-site (loss and traffic disruption of long-term external power supply), fuel With the support or the like from stockpiles or external such as oil, it is a loss safety of the reactor and spent fuel poo Correspondence is take it so as not I.

Commentary -20. In the IAEA SSG-21, lava flow, was of the dynamic and static load and its high temperature (up to 1200 ° C)

Eye, a direct influence. Influence of lava flow is usually can be mitigated by measures by the design and operation You are that it is not. , Reactor of stopping, of appropriate nuclear fuel transportable Policy out, etc. is carried out.

6.4) Volcanic debris avalanche, landslide and slope failure

(1) **Debris Avalanche, Impact of Landslides and Slope Failures**

(a) **direct impact**

Of debris occur as a result of the volcanic system collapse Who is, by a very large amount of sediment (case, the number Ten or more cubic kilometers) includes speed is fast, and to reach equivalent distance (see Table 1) There is a possibility that. Such a phenomenon is young destroy the engineering structures in the path as well as the lava flow Properly be buried. Such debris avalanche, the direct impact of landslides and slope failures design versus Since the response is not possible, to the rich exclusion criteria.

(b) **indirect effects**

Debris avalanche, landslides and slope failures affect range as compared to the pyroclastic and fire 砕密 degree of flow narrow But it also be considered that there may occur the damming and flooding rivers by this phenomenon There is a need that. In addition, affect the social infrastructure around nuclear power plants, damage to the power grid That access restrictions event of long-term to the loss of external power supply and nuclear power plants by may occur also considered There is a need to take into.

(2) debris avalanche, impact assessment of the nuclear power plant due to landslides and slope failure Debris avalanche, land for each volcano that activity possible during the operation period of the nuclear power plant In the evaluation of the slip and slope failure, actual sediment of similar volcanic, and avalanche flow stationary mode Using the collected information from the maximum expected amount of outflow distance, and soil compost in nuclear power plants Considering the thickness of the product, and then left and right source regions of the terrain, the length of the outflow speed, the amount and thickness That shows the impact in terms of range, etc. of parameter values to a nuclear power plant, the propriety of design support Evaluate. (Commentary -21)

(3) **verification matter of indirect effects**

In consideration of the impact of nuclear power generation off-site (loss and traffic disruption of long-term external power supply), fuel With the support or the like from stockpiles or external such as oil, it is a loss safety of the reactor and spent fuel pool Correspondence is take it so as not I.

Commentary -21. IAEA SSG-21 Oite, when the debris avalanche, landslides and slope failures occurred in the vicinity of nuclear power plants and original 16 If you want to directly affect the nuclear power plants, these effects can be mitigated by measures by the design and operationYou have to be not

6.5) Volcanic debris flow, mud flow and flood

(1) volcanic debris flows, volcanic mud flow and the impact of flooding

(a) direct impact

Debris flow generated by volcanic events, volcanic mud flow, and flooding caused along with these The flow rate is fast, the amount of discharge is large and the flow rate is large, it is possible to reach considerable distances. In addition, since such a phenomenon is dependent on the volcanic ejecta, after volcano eruption, in a few decades from a few months There be sustained over. Destruction young properly engineering structures in similarly route and lava flow I be buried.

(b) indirect effects

Volcanic debris flows, lahars and floods, affect the social infrastructure around nuclear power plant Is, access restrictions event of long-term to the loss of external power supply and nuclear power plants due to damage of the power grid is issued It may also be necessary to take into account that can be without.

(2) Impact assessment of volcanic debris flow, to nuclear power plants due to volcanic mudflows and floods

The volcanic debris flow for each volcano that activity possible during the operation period of the nuclear power plant, In the evaluation of volcanic mud flow and flood, and information about the actual sediment from the volcano that is similar in the vicinity, And using the debris flow stationary model, the debris flow and volcanic mud flow for nuclear power plant of sediment The maximum expected amount, considering the outflow distance and thickness, the flow for each terrain volcano that can And shows the influence of the nuclear power plant discharge amount from the point of view of range, etc. of influence parameter values, I evaluate the design correspondence of propriety. In addition, debris flow, mudflow nest caused by pyroclastic around site That possibility is there, in which case, grounds surrounding terrain, the impact on the basis of the deposition amount of pyroclastic of 6.1 Evaluation that the. (Commentary -22)

(3) **Items to be confirmed**

(a) the direct impact of verification matter

That volcanic debris flows, lahars and floods do not reach the nuclear power plant. However, to reach This shown that volcanic debris flow, characteristic of volcanic mud flow and flood, that design correspondence is possible by the scale
Door if possible, is not limited to this.

(b) verification matter of indirect effects

In consideration of the impact of nuclear power generation off-site (loss and traffic disruption of long-term external power supply), fuel With the support or the like from stockpiles or external such as oil, it is a loss safety of the reactor and spent fuel pool Correspondence is take it so as not I.

Commentary -22.IAEA SSG-21 Oite, debris flow and sediment of volcanic mud flow, very large thickness (for example, a few tens of meters

Some can reach Le). Given the impact of the amount of extensive and to nuclear power plant due to this, soil and stone Liu, the effects of volcanic mud flow and floods, generally can not be mitigated by measures by design and operation, place
The protection measures in consideration and local in nuclear power plants and plant layout and design by case the location and have to be able to deal with these effects.

6-6-6. Ballistic fragments (ash deposits)

(1) Influence of the ballistic fragments

(a) Direct impact

Ballistic fragments which come from volcanoes flies with a velocity within a range from 50 – 300 m/s (at around the mouth), and their flight distance is determined by the function of particle (grain) diameter and the aerodynamic drag. This aerodynamic drag might get reduced behind shock waves caused by a large-scale eruption. Also, the number of ballistic fragments which might fall on the plant can be a significant amount. (See *Commentary 23)

(b) Indirect impact

The possibility of fire has to be considered since ballistic fragments are usually of a very high-temperature. Secondary effect (such as a fire) might affect the social infrastructure around the plant. It has to be considered that situations such as a long-term loss of off-site power caused by damage of power grid system, and access limitation to the plant, might occur. (See *Commentary 24)

(2) Effect assessment of the ballistic fragments to the plant

In the hazard assessment of ballistic fragments to each volcanoes which have a possibility of activity in the period of the plant's operation, information about the longest distance and the largest size of ballistic fragments produced from explosive eruption of similar volcano in the past, is used. We indicate influence to the plant in consideration of the biggest size and amount of ballistic fragments, explosion pressure, fragment's density, variation in output angle and relevant parameter, then evaluate availability of response with the plant's design. (See *Commentary 25)

(3) Points to be checked

(a) Check points of the direct impact

To check whether ballistic fragments reach to the plant, provided, however, that if it is possible to be prepared within the plant's design to deal with reaching ballistic fragments (in terms of their size and amount etc.).

(b) Check points of the indirect impact

In consideration of influence to outside of the plant (such as long-term loss of off-site power, and paralyzing traffic), it should be checked how to handle to maintain safety of the reactor and the pool of spent nuclear fuel, through the use of stock of fuel and some support from outside etc.

*Commentary 23 Ballistic fragments are contrastable with impacts of flying fragments blown by a tornado or aircraft collision.

*Commentary 24 Fire can be assessed as an outside hazard (such as a forest fire).

*Commentary 25 The IAEA SSG-21 says; the influence of ballistic fragments cannot be absorbed / eased by any measures (response) with the plant's design and its operation, in principle. In some cases, however, it can be prepared to the influence through the plant's layout, design, operation, and some measures (response) for protection of the plant.

6-6-7. Volcanic gases

(1) Influence of the volcanic gas

(a) Direct impact

Affects of the volcanic gas are; suffocation, toxicity, and corrosion. A large amount of volcanic gas might be evolved when a volcano erupts. Sometimes, volcanic gas can be evolved from the mouth of some volcanoes even during the period they are not erupting. Moreover, the gas can be spreading through the soil around vent (mouth) of the volcano.

(b) Indirect impact

The volcanic gas contains gas harmful to biology (such as carbon monoxide, sulfur dioxide, hydrogen fluoride, etc.). Activity of residents who live around the plant and their life is restricted because of the gas's harmful characteristic features. It affects mechanical systems also. It has to be considered that volcanic gas affects people around the plant and the social infrastructure, and long-term access limitations to the plant might occur. (See *Commentary 26)

(2) Effect assessment of the volcanic gas to the plant

In the assessment of the volcanic gas to each volcanoes which have possibility of activity in the period of the plant's operation, we define the distance between the potential source of generation of volcanic gas and the plant, through the use of observational data of gas concentration measurements in possible volcanoes, and some information collected from similar volcanoes. Or on the assumption that some possible volcano erupts volcanic gas, we estimate impact of volcanic gas by using atmospheric dispersion models with some tentative value of mass flux of volcanic gas. Then we indicate the influence to the plant and evaluate availability of response with the plant's design.

(3) Points to be checked

(a) Check points of the direct impact

To have measures to take for avoiding serious influence to worker's activity if the volcanic gas reaches to the plant.

To have proper measures for preventing important safety facilities from losing their functions by accumulated volcanic gas.

(b) Check points of the indirect impact

In consideration of influence to outside of the plant (such as long-term loss of off-site power, and paralyzing traffic), it should be checked how to handle to keep safety of the reactor and the pool of spent nuclear fuel, through the use of stock of fuel and some support from outside etc.

Commentary 26 The IAEA SSG-21 says; the influence of volcanic gas can be absorbed / eased by any measures (response) with the plant's design and its operation.

6.8) Opening of new vent (mouth)

6-6-9. Seismic surges (Tsunami) and seiche

(1) Influence of the seismic surges and seiche

Volcanic eruption might cause seismic surges (Tsunami) and seiche. The influence by seismic surges and seiche induced by volcano is the same as that induced by earthquake.

(2) Effect assessment of the seismic surges and seiche to the plant

This is included in the effect assessment of earthquake and seismic surges.

(3) Points to be checked

It depends on the assessment of earthquake and seismic surges.

6-6-10. Atmospheric phenomenon

(1) Influence of the atmospheric phenomenon

Explosive volcanic eruption might cause potentially dangerous atmospheric phenomenon. Excessive pressure by atmospheric vibration, in many situations, might be able to reach a few kilometers away from the point of volcanic material eruption. The type of eruption, which brings eruption column (smoke) and volcanic column (ash), generally come with high frequency lightning, and strong downburst.

(2) Effect assessment of the atmospheric phenomenon to the plant

Extreme atmospheric phenomenon by volcanic eruption is included in the effect assessment of tornado and lightning strike.

(3) Points to be checked

It depends on the assessment of tornado and lightning strike.

6.11) Land deformation

6-6-12. Volcanic earthquakes and related events

(1) Influence of volcanic earthquakes and related hazard

Generally, volcanic earthquakes and related events occur as a result of variation in the stress and strain (produced by ascent of magma toward the surface). Characteristic features of volcanic earthquakes are widely different from the ones of tectonic earthquake. Volcanic earthquakes can be massive (the top potential hazard on the whole) or can occur frequently (like few hundreds to few thousands-times a day).

(2) Effect assessment of volcanic earthquakes and related events to the plant

In the effect assessment of the volcanic earthquake and the related events to the plant, in consideration of the local ground condition of the plant, we determine / assess combination of the magnitude of volcanic earthquake causing the biggest ground motion in the plant, depth of epicenter, and distance from the plant. On the other hand, if it is possible to demonstrate that volcanic earthquake in the plant is considerably less dangerous than other quakes with other source, then volcanic earthquake events can be included in the assessment under Earthquake.

(3) Points to be checked

To check whether it is within the range of assessment of seismic design standard.

6.13) Abnormality of hydrothermal system and groundwater

7. Supplemental provisions

If some other method of assessment (which is not stated in this guide) are presented and they are regarded as adequate and valid, the methods are allowed to be used. Also, this guide will be revised with new knowledge and experience.

Attached material of Doc. 0023_05 (p.22 and 23 in the original document)

CHART 1: VOLCANIC EVENTS WHICH MIGHT INFLUENCE THE NUCLEAR POWER PLANT AND THEIR RELATED POSITION*52

VOLCANIC EVENTS	CHARACTERISTIC FEATURES OF POTENTIAL INFLUENCE TO THE NUCLEAR PLANT	DISTANCE TO THE NUCLEAR POWER PLANT
1. Pyroclastic fall deposit	static physical load, abrasive and corrosive particles in air and in water	*53
2. Pyroclastic density flow	dynamic physical load, overpressure of atmosphere, impact of ballistic fragments, temperature over 300 degrees, abrasive particles, toxic gas	160km
3. Lava flow	dynamic physical load, dam for flood and water, temperature over 700 degrees	50km
4. Volcanic debris avalanche, land slide and slope failure	dynamic physical load, overpressure of atmosphere, impact of ballistic fragments, dam of water, and flood	50km
5. Volcanic debris flow, mud flow and flood	dynamic physical load, dam of water, and flood, floating particle in water	120km
6. Ballistic fragment (ash deposits)	collision of particles, static physical load, abrasive particles in water	10km
7. Volcanic gas	toxic and corrosive gas, acid rain, gas-filled lakes, contamination of water	160km
8. Opening of new vent (mouth)	dynamic physical load, ground deformation, volcanic earthquakes	*54
9. Seismic surges (Tsunami) and seiche	flooding of water	*55
10. Atmospheric phenomenon	dynamic overpressure, lightning strike, downburst wind	*4
11. Land deformation	ground displacement, subsidence or uplift, slope, landslide	*4
12. Volcanic earthquake and related events	continuous micro-motion, multiple impacts	*4
13. Abnormality of hydrothermal system and groundwater	hot water, corrosive water, contamination of water, flooding and upwelling, hydrothermal alteration, landslide, mutation of karst and thermal karst, rapid shift of water pressure	*4

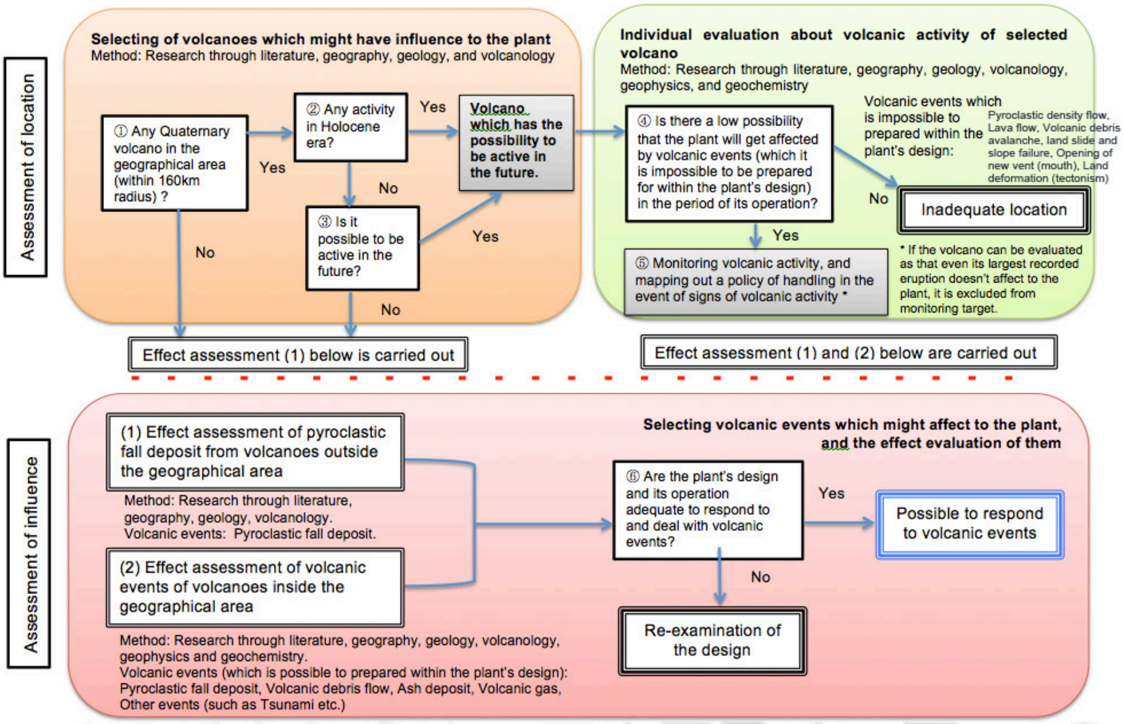
*52 If the distance between the nuclear power plant and centre of eruption is shorter than the figures stated on the positional relation in this chart, the plant will be affected by volcanic events.

*53 Regarding pyroclastic fall deposit, volcanic ash shall fall in an equivalent mass & thickness to that of the ash obtained from research in/around the plant, regardless of source of eruption.

*54 The possibility of opening of new volcanic vent (mouth) is evaluated in the period of the plant's operation.

*55 These events caused by volcanic activity are individually evaluated, regardless of their position in relation to the nuclear power plant.

Figure 1: Basic flowchart for effect assessment of volcanoes affecting the nuclear power plant



APPENDIX II

TITLES OF

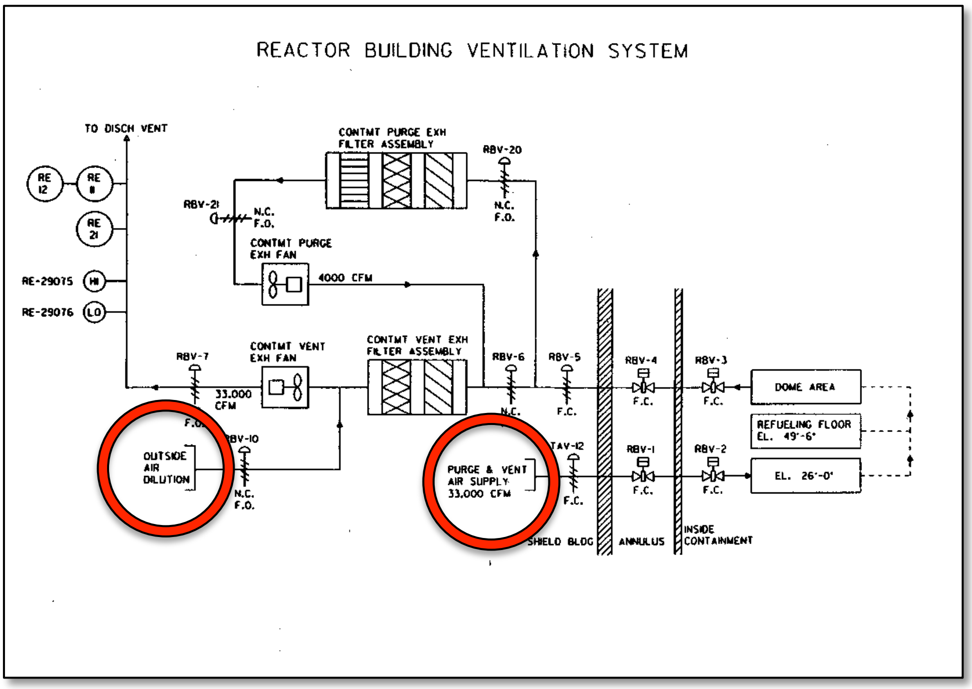
NRA SAFETY GUIDES NEWLY DEVELOPED AND/OR STRENGTHENED

(UNOFFICIAL TRANSLATION FROM THE ORIGINAL JAPANESE LANGUAGE VERSION)

(1) VOLCANO EVALUATION GUIDE
(2) TORNADO EVALUATION GUIDE
(3) EXTERNAL FIRE EVALUATION GUIDE
(4) INTERNAL FLOODING EVALUATION GUIDE
(5) INTERNAL FIRE EVALUATION GUIDE
(6) EVALUATION GUIDE FOR MEASURES TO PREVENT CORE AND CV DAMAGE
(7) EVALUATION GUIDE FOR MEASURES TO PREVENT FUEL DAMAGE IN THE SPENT FUEL POOL
(8) REVIEW GUIDE FOR RADIATION EXPOSURE EVALUATION REGARDING THE HABITABILITY OF THE CONTROL ROOM AND THE EMERGENCY OPERATIONS CENTRE
(9) REVIEW GUIDE FOR GEOLOGY AND GEOLOGICAL STRUCTURE INVESTIGATION AT AND AROUND THE SITE
(10) REVIEW GUIDE FOR DESIGN-BASIS GROUND MOTION AND SEISMIC DESIGN PRINCIPLES
(11) REVIEW GUIDE FOR EVALUATION OF FOUNDATION GROUND AND NEARBY SLOPE STABILITY
(12) REVIEW GUIDE FOR CONSTRUCTION APPROVAL OF SEISMIC DESIGN
(13) REVIEW GUIDE FOR CONSTRUCTION APPROVAL OF ANTI-TSUNAMI DESIGN

APPENDIX III

TYPICAL REACTOR CONTAINMENT AND OTHER ESSENTIAL SERVICES AREAS VENTILATION AND PURGE SYSTEMS



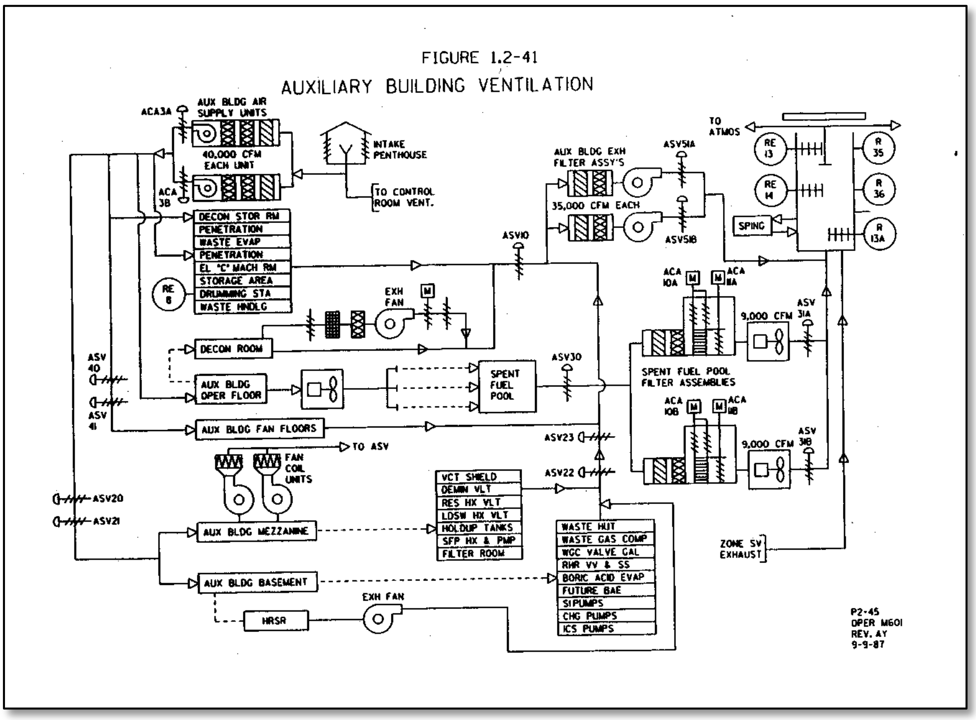
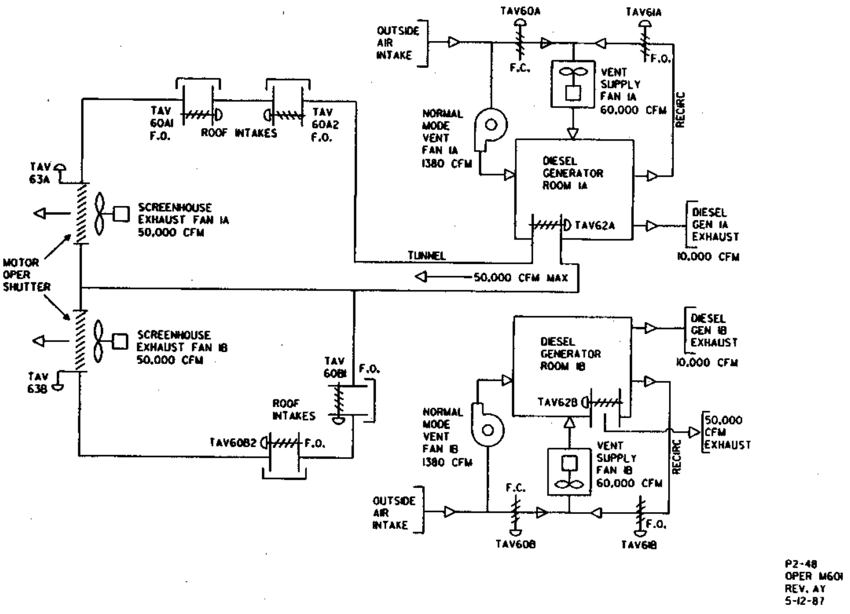


FIGURE 1.2-43

SCREENHOUSE AND DIESEL GENERATOR ROOMS VENTILATION



APPENDIX IV

EXTRACTS AND ANALYSIS OF THE NEW REGULATORY REQUIREMENTS APPLIED TO VOLCANIC EVENTS[8]

TABLE A EXTRACTS OF THE NEW REGULATORY REQUIREMENTS – APPLIED TO VOLCANIC EVENTS[8] ONLY

TOPIC/ISSUE	REQUIREMENT ETC	COMMENT	APPLICABLE AS VOLCANIC HAZARD TO SENDAI NPPS	COVERED IN NEW VOLCANO ASSESSMENT GUIDE [7]
PAGE 1 REGULATORY REGIME EXTANT PRE FUKUSHIMA-DAIICHI CATASTROPHE OF MARCH 2011				
Accident Recognition	Severe Accident Identification	Failure to identify and account for both severity and range/variability of external events and natural phenomena - Black Swan events ignored.	Applied to Sendai NPPs, both reactor and spent fuel ponds prior to July 2013 – continued to apply to spent fuel ponds when reactors and long ceased criticality.	Prior to Fukushima Daiichi, both regulator NIS and NPP operators may have complied with JEAG-2009 and IAEA[65] volcanic effect guides although, if they did, then the NRA was somewhat scornful about the depth of their individual involvement.[4]
Operator Responsibility	Defence-in-Depth Severe Accident Counter-measures	Certain foreseeable extreme events, including volcanic event effects not prepared for.	As above – regulator failed to demand and operator failed to provide for.	As above
Volcanic Hazard Assessment	Risk and Hazard Assessment	Risk assessments for volcano events had not been undertaken.	As above – regulator failed to demand and operator failed to undertake risk assessment.	As above
PAGE 2 NEW REGULATORY REGIME – POST JUNE 2012				
Application	Severe Accidents	To include severe accidents and to be applied retroactively and be enforced by 8 July 2013.	YES – capable volcanoes well within proximal and distal ranges with Sendai NPPs within ~40km	Section 5-5-1 refers to the *'plant's design limit'* but does not, either qualitatively or quantitatively, specify what the limits are. Similarly, S6 specifies that volcanoes should be further assessed if the volcanic effect exceeds the NPP's *'design limit'* but it fails to define how the plant limits are to be determined.
Volcanic Events	Future Occurrence Mitigation and Counter-measures	Operators to assume that volcanic events will occur in future. Measures against severe volcanic event must be included in nuclear safety case.	YES - Sendai at ~40km distant from the most active local volcano Mount Sakurajima yields significant tephra fall (amongst other volcanic effects) is a hazard that might affect plant nuclear safety, especially if there is a series of successive eruptions over time.	S3.3.3(1) requires all volcanoes with past eruption(s) in the Holocene era to be considered as *'capable'* - where it is assessed that there will no future (NPP lifetime) volcanic activity the it is assumed that a notional volcanic activity will occur with the same tephra deposition layer depth as found at any time during the Quaternary period.
Backfitting	Existing Licensed NPPs	Backfitting to existing NPPs to enforce latest regulatory requirements.	YES - applies to both Sendai NPPs.	S1.2 specifies application to existing sites – the IAEA SSG-21 Safety Guide referred to states that the SSG-21 guide applies to existing NPPs retrospectively. Not clear if Guide and hazard assessment applies to decommissioning periods.
PAGE 5 PRINCIPLES OF NEW REGULATORY REGIME				
Concept	Defence-in-	Countermeasures against	In principle YES, but definitions of	S1.1 in the General Provisions is the only

Principle	Depth & Design-Basis	natural phenomena (volcanoes) significantly enhanced.	*'design-basis'* for each volcanic effect hazard is unclear.	mention of *Design-Basis* throughout the NRA Volcanic Effects Assessment Guide – the JEAG 4625 guide referred to in the Assessment applies to the site selection of new NPPs.[66]
Defence-in-Depth	Emphasis on Defence-in-Depth	Multi-layered and diverse protective measures to be installed.	In principle YES, but definitions of *'Defence-in-Depth'* for each volcanic effect hazard is unclear.	Defence-in-Depth not referred to ot defined in Volcanic Effect Assessment.
Design-Basis	Enhanced Design-Basis	Significantly enhance design-basis with protective measures against natural phenomena (volcanoes) to inhibit common cause failure.	In principle, YES - a series of *Design-Basis* events could be established for Sendai NPPs, that is setting out the 'design-basis' limits and conditions to match (ie countermeasure and/or mitigation actions) each volcanic hazard that has not been screened out on probability and distance from the eruption source – one example of a *design-basis* would be to provide resources to countermeasure clear the roofs of tephra ash layer thickness matched to the safe superimposed load of the roof structures (ie 15cm).	S6.6.1 deals with tephra fallout and generally identifies both *direct* and *indirect* impacts, including LOOP, but it does so only in a very generalised way without establishing any limits and conditions with which to prescribe the design-basis.
Performance Based	Site/Facility Specific	Operator required to install appropriate design and procedural countermeasures and/or mitigation measures to match specific NPP.	YES – the following general areas of design amendment and improvement are likely to be required at Sendai NPPs (related to airborne tephra fall only): a) tephra layer superimposed loading: i) flat roofs ii) side wall loading iii) external tanks covers iv) equipment covers b) tephra clogging and blockage: i) gutters downpipes and drains ii) main sea inlet intake screens and racks iii) reactor auxiliary cooling seawater system iv) reactor auxiliary cooling system 1) seawater pump 2) heat exchanger v) air filters and coolers 1) air conditioning 2) ventilation vi) emergency diesel generators 1) aspiration filters 2) room filters 3) main engine cooling coils 4) oil lubricant cooling coils c) tephra abrasion and seizure: i) machinery and pumps ii) main steam relief valves iii) turbo-generator cooling pumps iv) external electrical switch-gear d) tephra wet film flashover i) substation yard ii) off-site transmission and distribution grids e) etc	The influence of, and hence the resources required to overcome and/or mitigate the tephra fall, are addressed in S 6-6-.1(1), (2) and (3), although not in any great detail. However, the possibility of LOOP conditions are recognised although the commencement time and length of LOOP are not specified in terms of hard-and-fast limits and conditions. Human resource requirements for tephra ash clearance, filter changes and other manual task are not included, although these collectively could be a very significant resource commitment, especially when transporting personnel to the NPP site may present difficulties with high rates of tephra fall and ash deposition. Off-site Emergency service provisions are not specified – availability of off-site emergency services could be problematical, especially if these are prioritised elsewhere.

PAGE 6 BASIC POLICIES AGAINST SEVERE ACCIDENTS AND TERRORISM				
Redundancy	Crucial Facilities	Deployment of mobile facilities, such as truck	YES - In anticipation of a prolonged LOOP, mobile generator sets may be	No specific provision other than anticipation of prolonged LOOP in S6-6-

	Enhance	mounted diesel generators to enhance reliability of permanent equipment.	required to be moved into ready positions outside the NNP site – it is not known if cabled connection to the Sendai NPPs is installed in contingency.	1.(1)(b) and S6-6-1.(3)(b)
PAGE 7 EXPANSION OF THE DESIGN CONSIDERATION AND ENHANCEMENT OF COUNTERMEASURES TO NATURAL PHENOMENA				
Common Cause	Design-Basis	Include natural phenomena into design consideration and design-basis.	YES - Common cause failure opportunities with a number of issues relating directly to airborne tephra, particularly filter clogging of, for example, both on-site and off-site stationed temporary mobile generator sets	Nothing specific.
PAGE 8 COMPARISON BETWEEN PREVIOUS AND NEW REGULATORY REQUIREMENTS				
Natural Phenomena	Consideration of Natural Phenomena	Consideration of natural phenomena now mandatory	YES – NRA's New Regulatory Guide on volcanic effects now requires account of this natural phenomena	General consideration of natural phenomena, including tephra fall included.
PAGE 13 COMMON CAUSE AND DESIGN BASIS				
Natural Phenomena	Common-Cause & Design-Basis 1st Stage Elimination Screening	Provide tailored Design-Basis to enhance against common-cause failures	Yes - setting of 160km screening criteria for pyroclastic flows and tephra ash fall on NPP and requirement for the operator to provide appropriate protective measures in advance.	Noting specific.

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