SAND2012-1226C

Overview of DOE/NNSA Consequence Management's (CM) Response to the Fukushima Dai-ichi Nuclear Power Station Releases

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SAND Report 2012-1226C

Sandia National Laboratories
Department 6631

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Great East Japan Earthquake

- Earthquake occurred March 11, 2011 @ 14:46 Local Time
- Earthquake Magnitude 9.0, Depth 24 km
- 4th Largest Recorded Earthquake
- Estimated energy released was 9.3E6 Mt of TNT
- Moved Japan 8 feet closer to the United States
- Shifted earth's axis 10 cm

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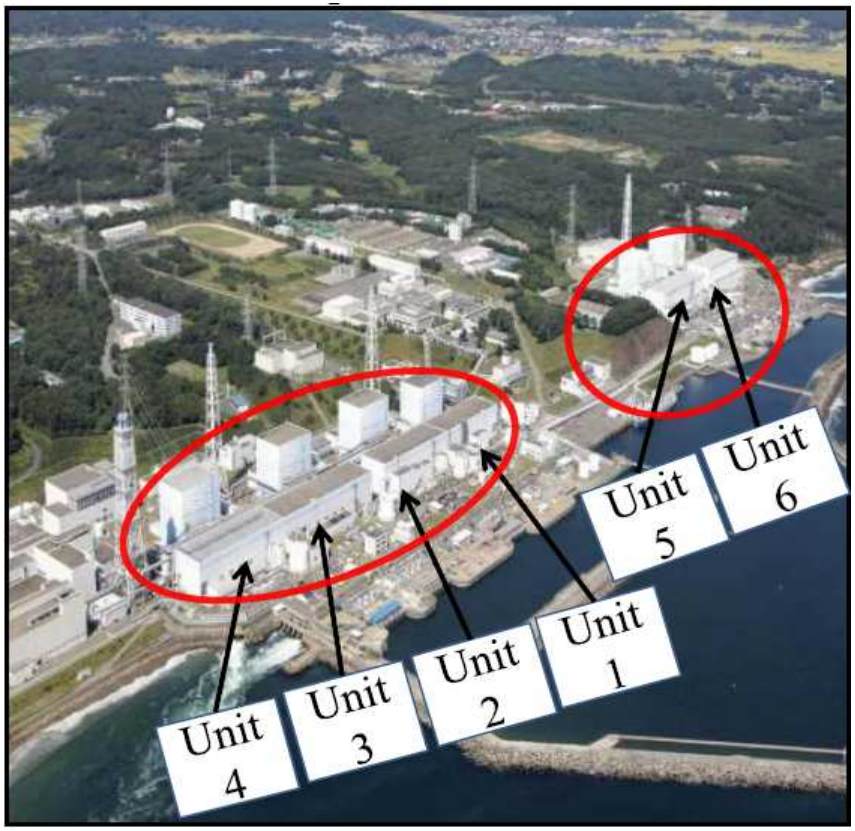
Big Tsunami

- **Wave Amplitude along Japanese Coast ~ 6 – 19 m (19 – 62 ft.)**
- **Run-up (Wash-up) Height ~ 7 – 38 m (23 – 125 ft.)**
- **~ 20,000 killed/missing due to earthquake and tsunami**

Fukushima Dai-ichi Nuclear Power Plant Site



- 6 Boiling Water Reactor Units at Fukushima Dai-ichi NPS site
- Each unit also had Spent Fuel Pool (SFP) with mix of old and "new" spent fuel.
- Units 1, 2 & 3 were at full power
- Unit 4 was de-fueled for re-fueling
- Units 5 and 6 were in cold shutdown for planned maintenance.
- All units were immediately shut down by automatic safety systems after earthquake.
- Tsunami wave (~14 m, 46 ft.) hit Dai-ichi site approximately 1 hr after earthquake.

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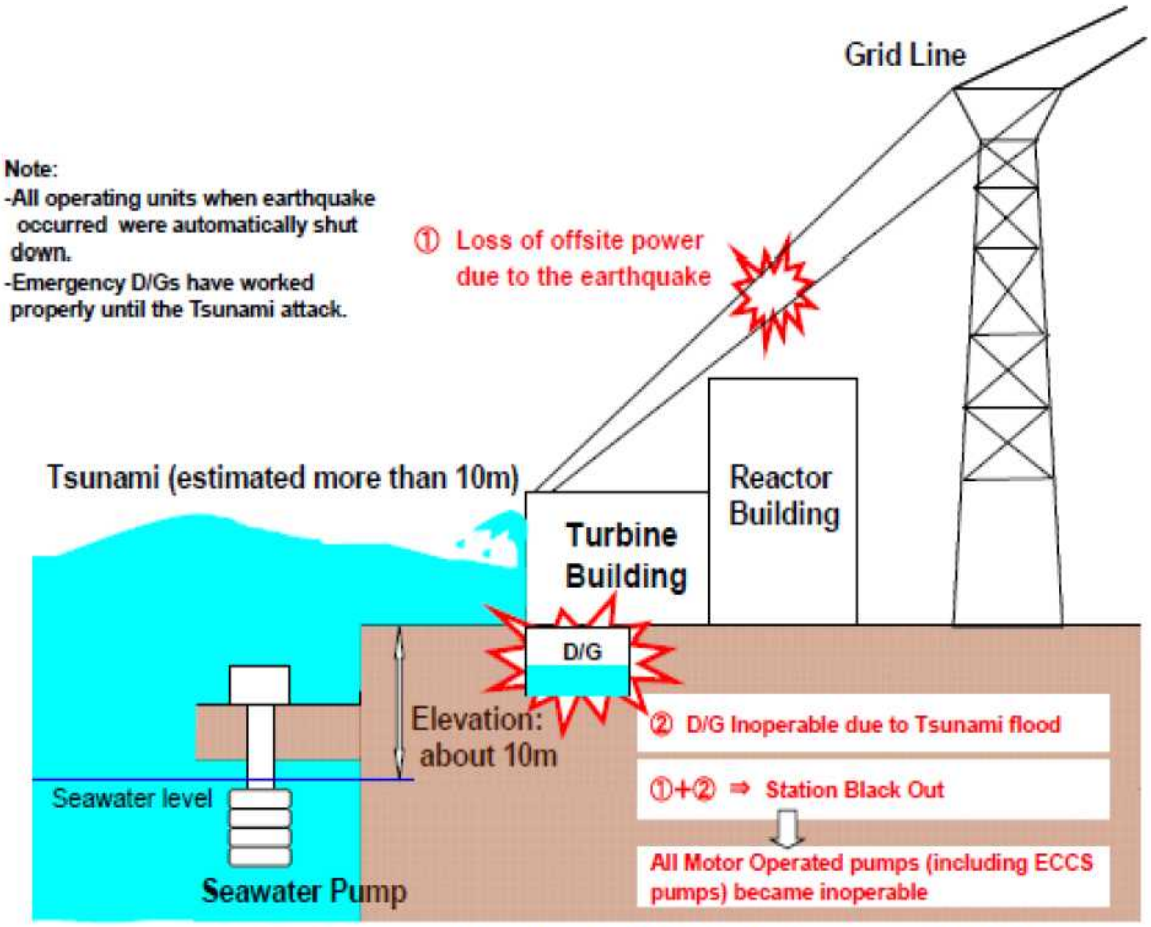
Root Cause of Damage



Source: Nuclear and Industrial Safety Agency (NISA)

- Off-site power to NPS site lost due to earthquake
- All emergency diesel generators disabled by Tsunami flood (generators were 10 – 13 m above sea level)
- Emergency battery power depleted after 8 hr
- Unable to cool fuel in reactors and spent fuel pools

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Decay Heat

During operation decay heat accounts for ~10% of reactor power

- After shutdown decay heat decreases as fission products decay away
- Within hours decay heat is down to 1% of operating power
- Still a significant source of heat for power reactors
- Without cooling decay heat can cause fuel to melt

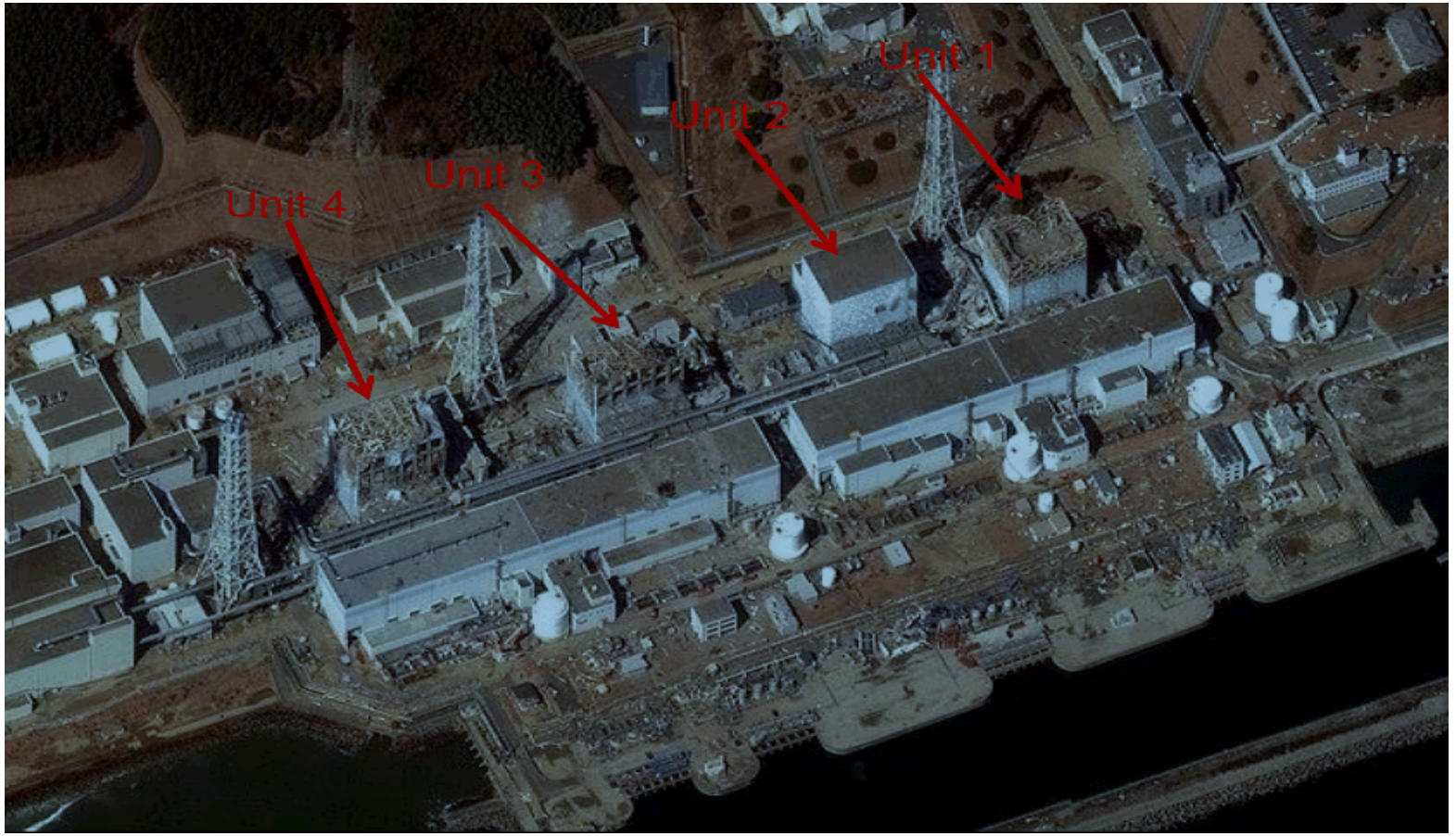
For a 1000 MWt reactor decay heat is:

- 70 MW immediately after shutdown
- 10 MW after 3 hours
- 5 MW after 5 days
- 1 MW after 2 months
- 100 kW after 1 year

Fuel Degradation

- Flow of cooling water stopped due to lack of power.
- Water boiled away and level in core dropped below top of fuel.
- Temperature increased caused fuel degradation.
  - Fuel cladding failed (rupture) releasing gaseous fission products
  - Zirconium in cladding oxidized in presence of water creating hydrogen gas (exothermic reaction producing more heat)
  - Fuel melt (how much???) releases fission products (Cs, I, Xe)
- Pressure buildup threatened containment structures.
- Operators manually opened valves to prevent over-pressurization of Primary Containment Vessel (PCV) releasing gaseous fission products (e.g., Cs-134 and 137, I-131) and hydrogen into reactor building.
- Hydrogen explosions in Units 1, 3 and 4 (SFP).

Hydrogen Explosions



What radionuclides and how much activity was released?

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Stabilization of Units 1 - 4

- Pumping of fresh water and seawater helped cool the reactors and spent fuel pools
- Boric acid was injected reactors to prevent meltdown
- N_2 was injected into PCV to reduce possibility of hydrogen explosions
- Eventually power was restored to pump water to cool the fuel

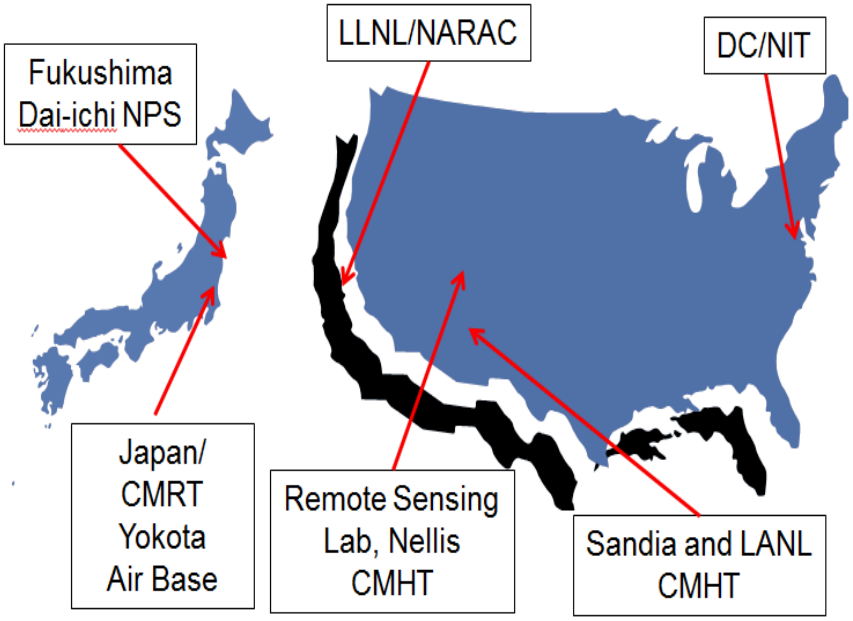
Public Protection Actions

- March 12: Government of Japan established mandatory evacuation zone for people living within a 20 km radius of the Fukushima Daiichi NPS and recommended shelter-in-place for people living within 20-30 km
- March 13: U.S. Embassy issued an advisory restricting travel US citizens within 80 km of the Fukushima NPS
- March 16: U.S. Embassy and U.S. Forces Japan (USFJ) authorized voluntary departure for dependents

DOE Support of Operation Tomodachi

March 11, 2011 DOE/NNSA activated the following assets

- **Nuclear Incident Team (NIT) in Washington, DC**
- **DOE/NNSA Consequence Management expertise from the U.S.**
- **Agency for International Development (USAID) Disaster**
- **Assistance Response Team (DART) in Tokyo**



- **National Atmospheric Release Advisory Center (NARAC) at**
- **Lawrence Livermore National Laboratory (LLNL)**
- **Consequence Management Home Team (CMHT) assets at Remote Sensing Laboratory (RSL), Sandia National Laboratories (SNL), LLNL and Los Alamos National Laboratory (LANL)**
- **The Radiation Emergency Assistance Center/Training Site (REAC/TS) in Oak Ridge, TN**

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DOE Support of Operation Tomodachi

Objectives of DOE Response:

- Assess consequences of release from Fukushima Dai-ichi Nuclear Power Station
- Assist the State Department mission to advise American citizens on protective action and evacuation guidelines.
- Assist DoD in its mission to safely conduct humanitarian assistance/disaster relief operations and to provide advice on departure/return of military dependents.
- Partner with the Government of Japan (GOJ) through the State Department to aid in developing guidelines for protection of the public potentially affected by the releases.

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DOE Timeline

March 14, 2011

- **At White House direction, DOE deployed a tailored CMRT and Aerial Measuring System (AMS) capability via military airlift to Yokota Air Base, Fusa, Japan**

March 16, 2011:

- **CM Assets arrive at Yokota AB and fly first AMS Test flight**

March 17, 2011:

- **Conducted first aerial measurement activities over plant and first field monitoring activities**

March 22, 2011:

- **Initial data published on DOE website**

DOE Assets

Field

- Monitoring and sampling
- Preliminary data assessment
- Product development

CMHT

- Detailed assessment
- Coordination of sample analysis
- Response to requests for information/assistance

NIT

- Initial command and control of deploying assets
- Coordination and communication for field assets and headquarters elements

Embassy

- Assessment interpretation for Ambassador
- Coordination of bilateral monitoring and assessment activities

CMHT Activities

- Consequence Management Home Team (CMHT) supported response 24/7 for ~6 weeks starting on 3/12/11 and then continued support with 1 shift for multiple weeks.
- CMHT included personnel from LANL, LLNL, RSL and SNL.
- Nuclear Incident Team (NIT) directed CMHT activities.
- DOE reported directly to the White House Office of Science and Technology Policy (OSTP) on issues of worst case planning for US interests and assessing real-time radiological conditions.
- OSTP had many questions and verified/scrutinized calculations and data products.
- OSTP requested numerous analyses and data products.
- CMHT personnel worked with personnel at the NIT, in the field, at the U.S. Embassy to Japan, Naval Reactors and U.S. Government agencies (e.g., OSTP, EPA, FDA).

CMHT Activities

- CMHT reviewed and assessed many thousands of data points, including: AMS data, in-situ measurements (e.g., gamma spectroscopy), air samples, soil samples.
- Evaluated cesium and strontium uptake by rice and the potential doses from eating contaminated rice.
- Evaluated potential doses to personnel in Guam, Hawaii, Alaska and West coast of U.S. from fallout.
- Worked with EPA, FDA, USDA etc. to assess U.S. impacts
- Evaluated potential doses from ingestion (e.g., reindeer milk).
- CMHT Assessment personnel did many one-off calculations.
- CMHT provided many data products, presentations and advice to the OSTP to enable White House to make protective action decisions.

What Role Did SNL Assets Fill?

- SNL assets led the technical details of the radiological assessments
- SNL assets led the Lab Analysis support (analysis, data management)
- At the direction of the White House, taking worst case release source terms provided by the NRC/MELCOR, worked with NARAC to model the plume dispersion and estimated potential doses to receptors in Tokyo, Guam, Hawaii, Alaska, and US West Coast
  - Challenge, this is a rapidly decaying and ingrowing mixture and so each day the key nuclides in the mixture change.
- Participated in many teleconferences with OSTP and the NIT to assess impacts to U.S. citizens in the U.S., its territories and Japan.
- Calculated potential worker doses from direct exposure, and airborne material to help protect all US personnel in the area.
- Assessed potential iodine thyroid doses to Japan and US locations.
- Performed numerous other radiological dose analysis requests.
- Dealt with sample data that was poorly collected and managed, extracted useful information and corrected the process as the response progressed.

Radionuclide Mixtures??

Preliminary Mixtures:

- Trans-Pacific (18 parent, 13 daughter, Total of 31 radionuclides)
- NRC Supercore mixture for reactors, SFPs and combination (45 parent, 133 daughter, Total of 178 radionuclides
- SNL Melcore Mixture for reactors and SFPs and combination (63 parent, 187 daughter, 250 radionuclides.

Final Mixture:

- AMS Test Line Mixture

Radionuclide	Relative Value by Activ...
^{134}Cs	3.37
^{136}Cs	0.949
^{137}Cs	3.29
^{137m}Ba	3.11
^{131}I	8.70
^{131m}Xe	9.57E-2
^{132}Te	40.6
^{132}I	40.6

Trans-Pacific FIREHOSE, Worst Case Source Term and Meteorology Prediction

- Dose projections performed to assess worst-case dose impacts to U.S. citizens outside of Japan.
- Unrealistic assumptions:
  - 40% Units1 & 3 core release
  - 100% Unit 2 core release
  - Constant wind direction to receptors

Location	96-hr Projected Dose (mrem)	1-Year old Child Thyroid Dose based on I-131 deposition (mrem)
Southern Alaska	4.79E-2	1.94E+3
Hawaii	7.99E-3	2.78E+2
Midway	3.09E-3	1.26E+2
Southern CA	7.52E-2	4.00E+3
Northern CA	7.64E-2	4.06E+3
Oregon	6.04E-2	3.06E+3
Washington (state)	5.24E-2	2.76E+3

- No projected dose exceeded U.S. Environmental Protection Agency guidelines for taking public protection measures (e.g., evacuation, sheltering, relocation).
- No projected dose exceeded U.S. Food & Drug administration guidelines for issuing potassium iodide (KI) to protect the thyroid.

Aerial Measuring System Activities

What Was Done?

- Surveys over US Bases
- Joint DOE and Government of Japan surveys
- Fixed wing and helicopter AMS systems utilized

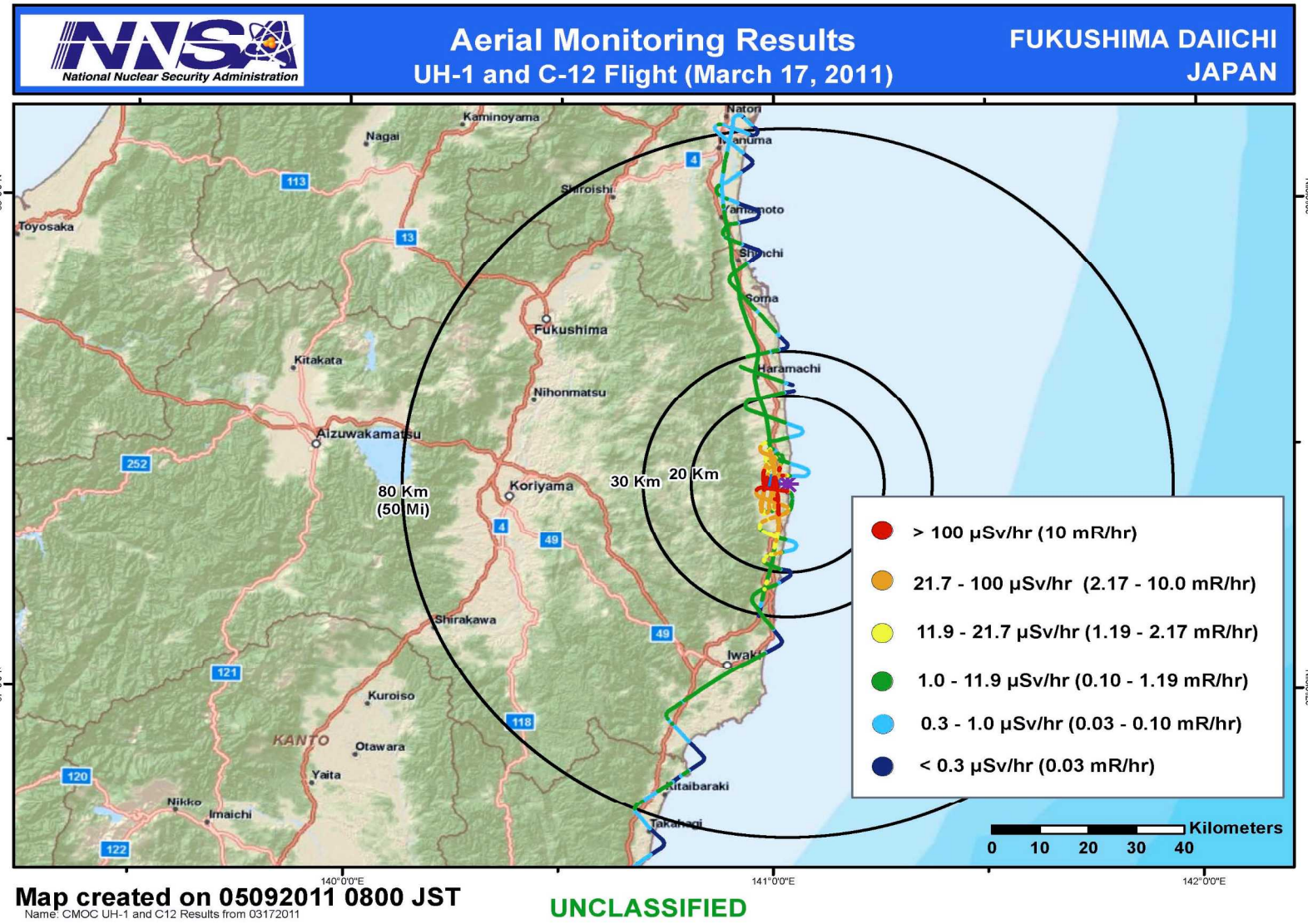
Why?

- Map ground deposition out to 80 km from damaged Fukushima Dai-ichi NPS
- Provide information to support evacuation, relocation and public protection decisions
- Provide information to support agricultural protective actions
- Support dose assessments.

Summary of Activities?

- 1 – 3 aircraft/day (more than 85 flights and 490 flight hours)

Maiden Aviation Voyage



Map created on 05092011 0800 JST

Name: CMOC UH-1 and C12 Results from 03172011

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Field Monitoring Activities

What Was Done?

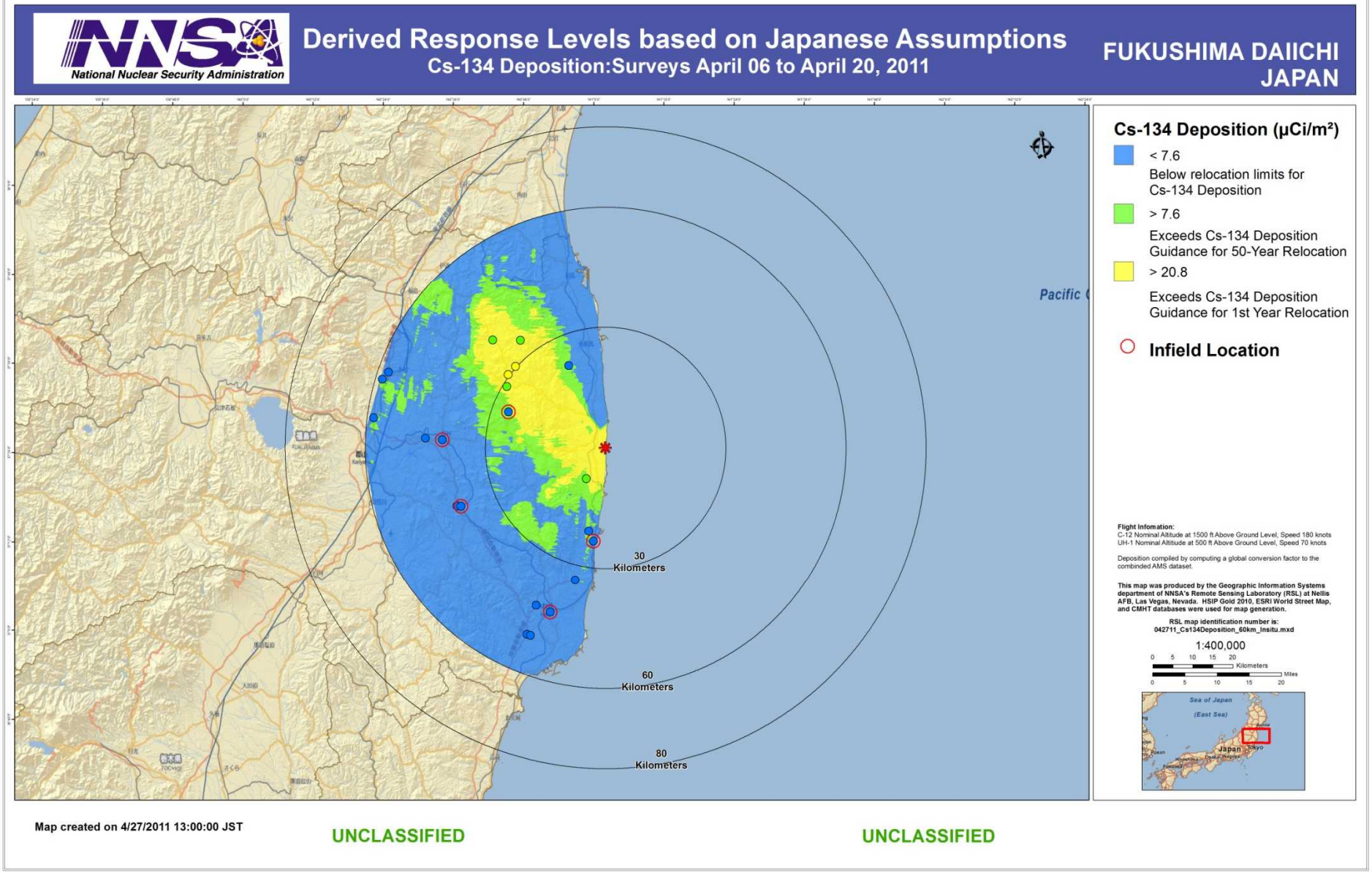
- Mobile monitoring
- In-situ measurements
- Exposure/dose rate measurements
- Air sampling
- Soil samples
- Swipe samples

Why?

- Calibrate AMS measurements
- Define radionuclide mixture
- Support radiological assessments
- Assess resuspension of deposited materials
- Assess horizontal and vertical and migration of radionuclides

Summary of Activities?

- > 620 air samples
- > 117 in-situ spectra
- > 141 soil samples


National Nuclear Security Administration
Derived Response Levels based on Japanese Assumptions
Cs-134 Deposition:Surveys April 06 to April 20, 2011
FUKUSHIMA DAIICHI
JAPAN
Cs-134 Deposition (µCi/m²)
< 7.6
Below relocation limits for Cs-134 Deposition
> 7.6
Exceeds Cs-134 Deposition Guidance for 50-Year Relocation
> 20.8
Exceeds Cs-134 Deposition Guidance for 1st Year Relocation
Infield Location
30 Kilometers
60 Kilometers
80 Kilometers
Pacific
Flight Infomation:
C-12 Nominal Altitude at 1500 ft Above Ground Level, Speed 180 knots
UH-1 Nominal Altitude at 500 ft Above Ground Level, Speed 70 knots
Deposition compiled by computing a global conversion factor to the combinded AMS dataset.
This map was produced by the Geographic Information Systems department of NNSA's Remote Sensing Laboratory (RSL) at Nellis AFB, Las Vegas, Nevada. HSIP Gold 2010, ESRI World Street Map, and CMHT databases were used for map generation.
RSL map identification number is:
042711_Cs134Deposition_60km_Insitu.mxd
1:400,000
0 5 10 15 20
Kilometers
Miles
0 5 10 15 20
Sea of Japan
(East Sea)
Japan
Tokyo
Map created on 4/27/2011 13:00:00 JST
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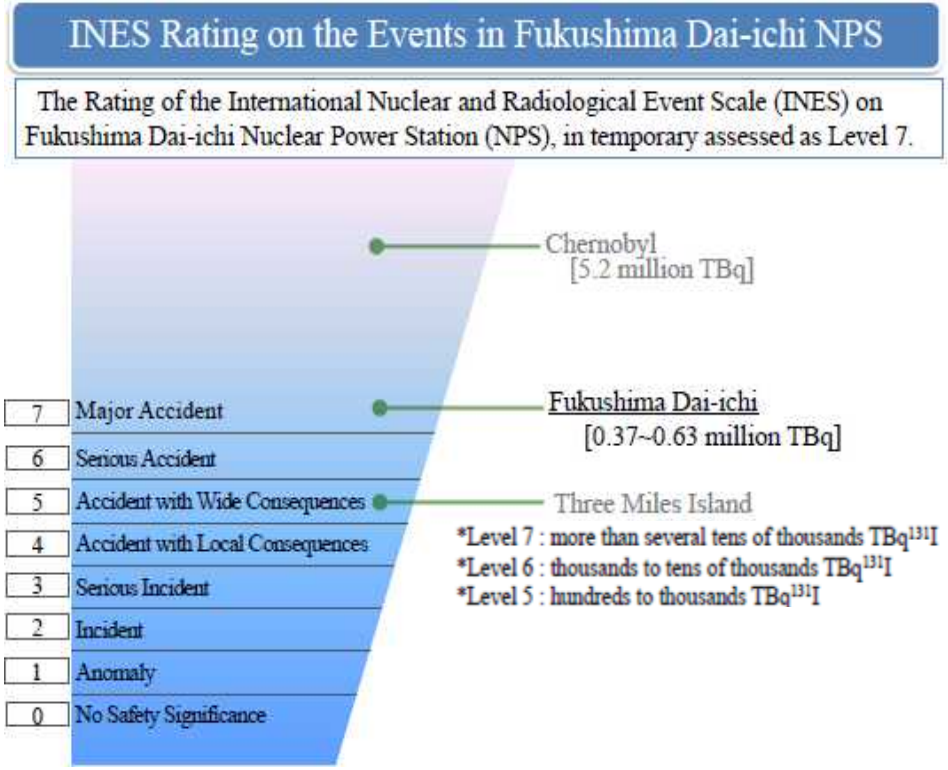
Estimated Releases

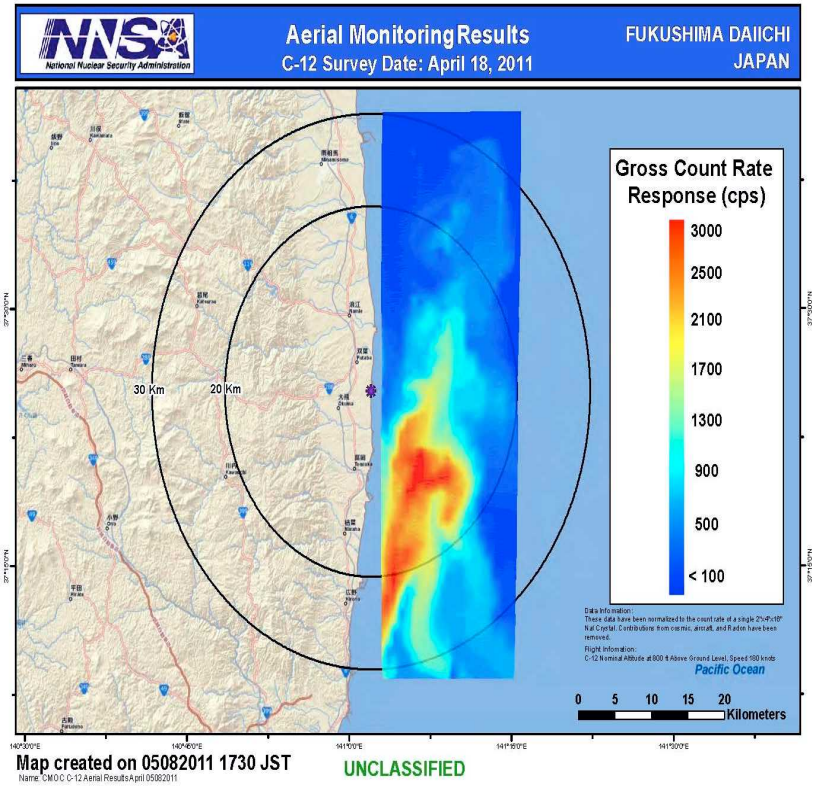
Nuclide	NISA[1]	NSC[2]	Chernobyl
I-131	$1.3X10^{17}$ Bq	$1.5X10^{17}$ Bq	$1.8X10^{18}$ Bq
Cs-137	$6.1X10^{15}$ Bq	$1.2X10^{16}$ Bq	$8.5X10^{16}$ Bq

[1] Nuclear and Industrial Safety Agency

[2] Japan Nuclear Safety Commission



Fortunately the diurnal winds pushed much of the radioactive material out to sea



Worker Radiation Doses

Safety of On-site Workers

The Japanese Government closely supervises on-site workers' health conditions, limiting the level of their maximum exposure to radiation to 250mSv.
No workers in Fukushima NPS have been exposed to 250mSv or more.

Emergency Dose Limit

mSv	JAPAN
emergency dose limit	100 ↓ 250 (limit raised for Fukushima emergency workers)

Ministry of Health, Labour and Welfare, Nuclear and Industrial Safety Agency, ICRP,

Workers Exposed to Radiation in Fukushima Dai-ichi NPS, as of April 5

level of exposure	number of workers
more than 100mSv	21
more than 250mSv	0

Nuclear and Industrial Safety Agency

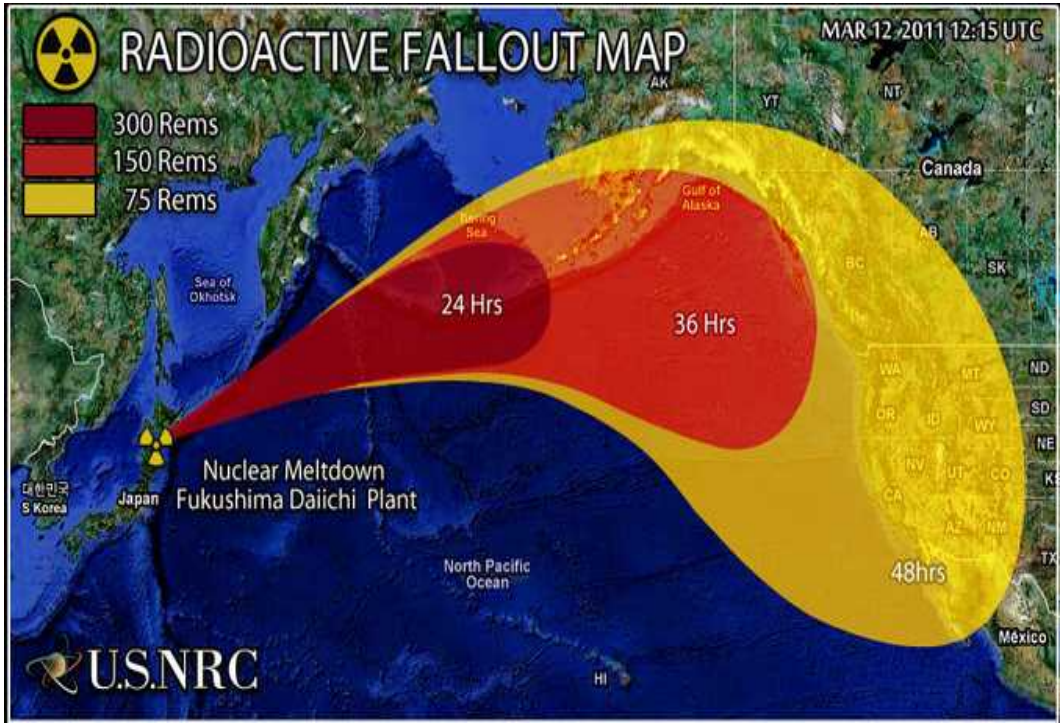
*On March 24, three workers exposed to more than 170mSv were hospitalized, but were released four days later after no health problems were found.

- **Heroic efforts by many Japanese workers**
- **No workers have died because of radiation exposures**

FEARMONGERING

- After Fukushima, California drugstores sold out of potassium iodide (or KI) – a potentially hazardous drug that protects the thyroid gland from absorbing radioactive iodine.
- According to Jessica Wehrman, from the American Association of Poison Control Centers, there have been at least 33 calls to poison control centers from people suffering negative side effects after exposure to KI. Symptoms include irritability, dizziness, drowsiness, nausea, vomiting, and tachycardia – a condition that causes the heart to beat faster than usual. (RDTN.org, 4/1/11)

DSI GLOBAL VIEW



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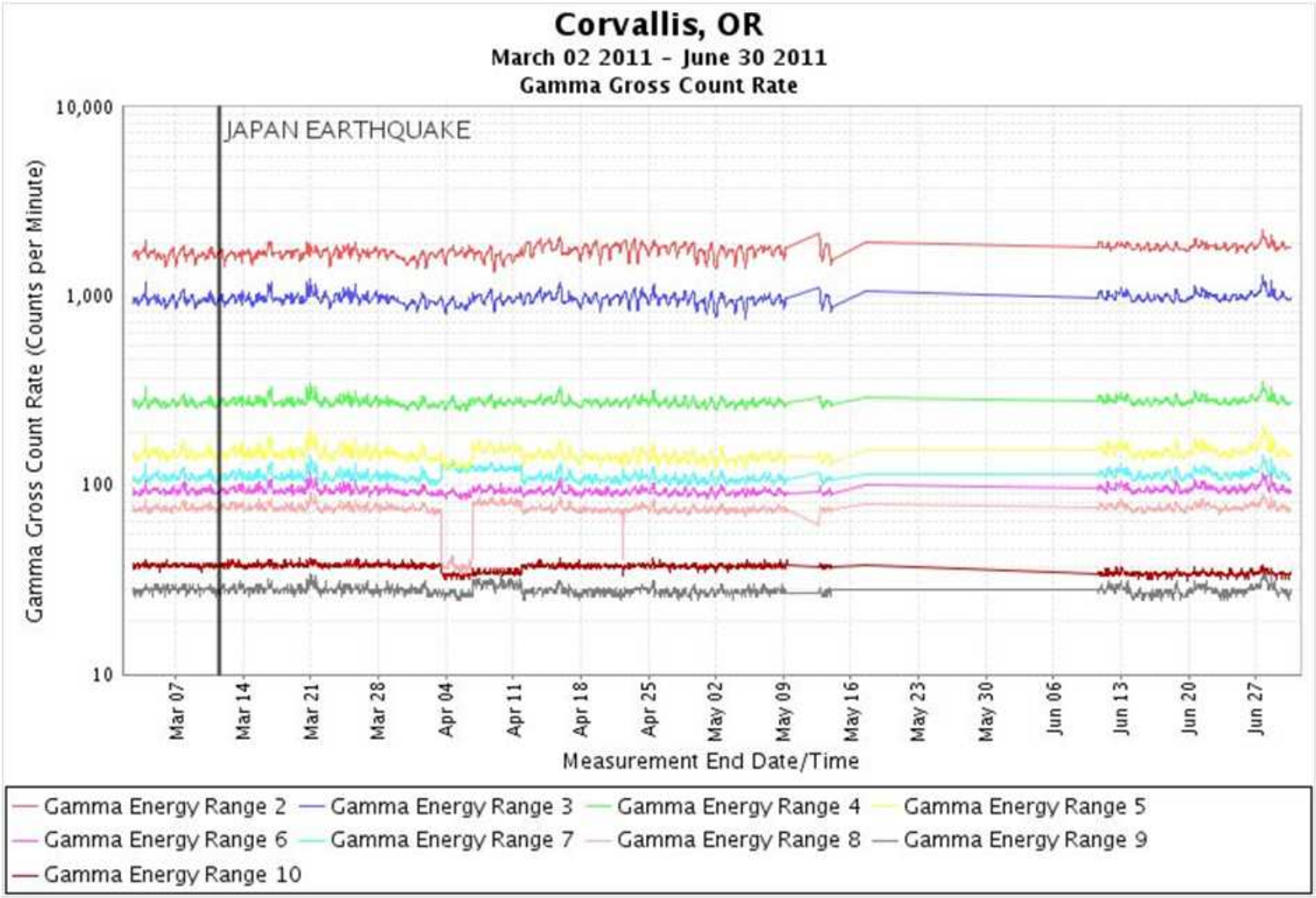
Real Data from EPA's RadNet Monitors



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Confounding Factors

- 15 hr time difference between teams in Japan and New Mexico.
- Japanese regulations were not understood
- Insufficient staffing led to burnout
- Massive amounts of data were available for review and assessment.
- Management of data flow and communication (email) was very difficult
- It was difficult to get current data on the actual status (health) of the reactors
- Multiple releases occurred under varying weather (snow, rain, sunshine) and wind conditions
- Difficult to perform accurate radiological assessments for quite some time because the radionuclide mixture and released activities were not known

Confounding Factors

- Command and Control was overwhelmed, everything was given top priority
- Leadership struggled to coordinate taskings and current status of CM assets at multiple laboratories in the U.S. and multiple locations in Japan
- The CMHT was put under a lot of pressure to produce assessments and data products too quickly, and therefore, QA/QC measures were not always adequate
- Complex terrain challenged models to predict and explain deposition patterns
- Many different individuals and agencies making their own predictions

Continuing Activities

- USFJ and Government of Japan to continue monitoring activities as needed
- Japanese trained and equipped to fly DOE AMS
- Japanese equipped with an enhanced laboratory analysis capability
- USFJ trained & equipped to fly contingency AMS
- DOE continues to support Japanese and USFJ from Home Team

QUESTIONS?

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Extra slides

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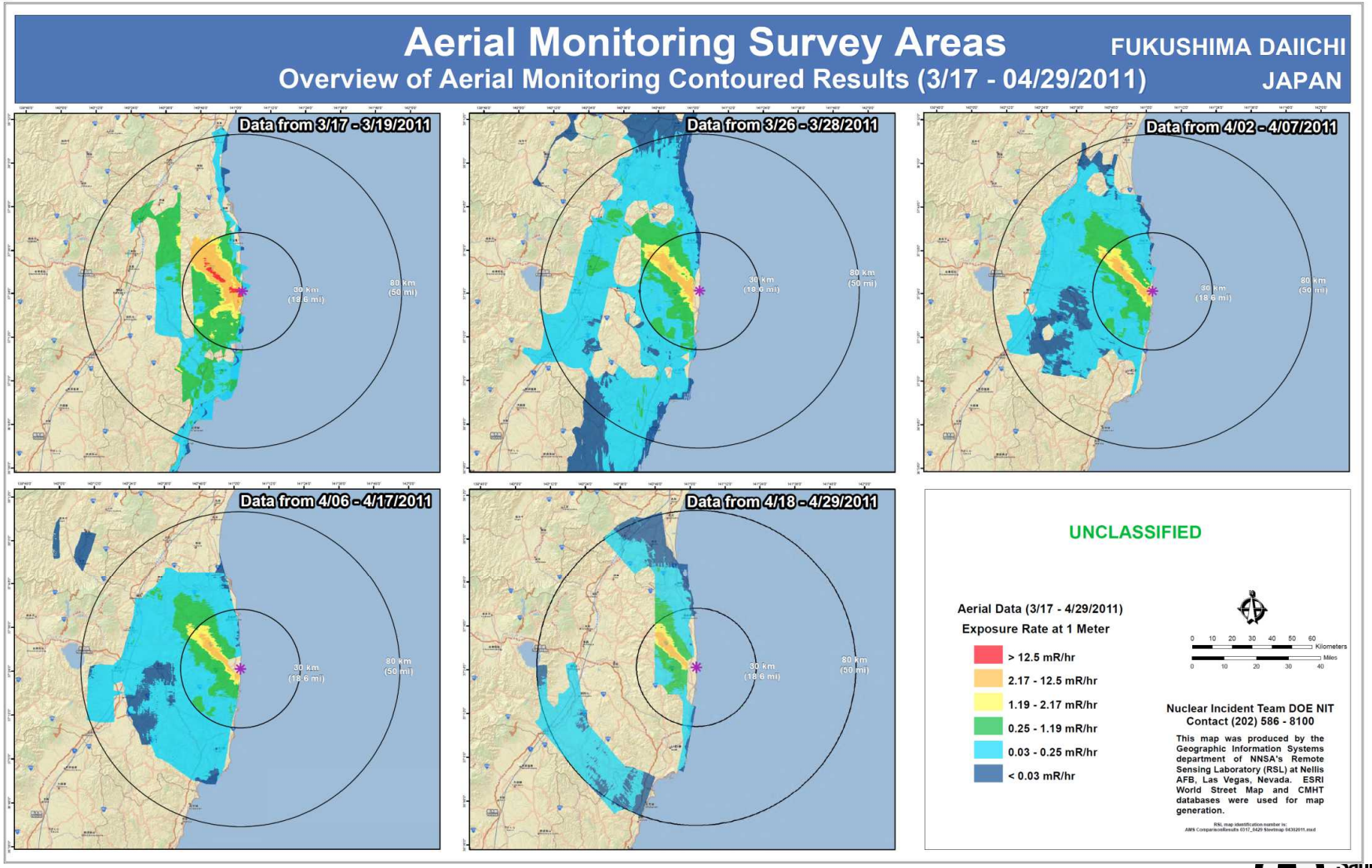
Then and now…


Aerial Monitoring Survey Areas
FUKUSHIMA DAIICHI
Overview of Aerial Monitoring Contoured Results (3/17 - 04/29/2011)
JAPAN
Data from 3/17 - 3/19/2011
Data from 3/26 - 3/28/2011
Data from 4/02 - 4/07/2011
Data from 4/06 - 4/17/2011
Data from 4/18 - 4/29/2011
30 km (18.6 mi)
80 km (50 mi)
UNCLASSIFIED
Aerial Data (3/17 - 4/29/2011)
Exposure Rate at 1 Meter
> 12.5 mR/hr
2.17 - 12.5 mR/hr
1.19 - 2.17 mR/hr
0.25 - 1.19 mR/hr
0.03 - 0.25 mR/hr
< 0.03 mR/hr
0 10 20 30 40 50 60 Kilometers
0 10 20 30 40 Miles
Nuclear Incident Team DOE NIT
Contact (202) 586 - 8100
This map was produced by the Geographic Information Systems department of NNSA's Remote Sensing Laboratory (RSL) at Nellis AFB, Las Vegas, Nevada. ESRI World Street Map and CMHT databases were used for map generation.

Cesium Deposition and Exposure Rate DRLs for 4/25/11 Based on Japanese Assumptions

The table below provides the Deposition Derived Response Levels and the Exposure Rate DRLs for the 1st-Year, 2nd-Year and 50-Year Time Phases for the AMS Calibration Test Line Source Term.

- The source term was assumed to have been deposited on 3/16/11
- The 1st-Year and 50-Year Time Phases start on 4/25/11
- The 2nd-Year Time Phase starts on 4/25/12
- The 1st-Year DRLs are based upon a dose of 2,000 mrem over the 1st Year*
- The 2nd-Year DRLs are based upon a dose of 500 mrem over the 2nd Year *
- The 50-Year DRLs are based upon a dose of 5,000 mrem over 50 years *

Date	Cs-134 ($\mu Ci/m^2$)	Cs-137 ($\mu Ci/m^2$)	Exposure Rate DRL (mR/hr)
1St- Year	20.83	21.17	0.48
2nd-Year	7.62	7.72	0.18
50-Year	7.58	7.68	0.18

* The 1st-Year, 2nd, and 50 year DRLs are based upon a dose of 2,000 mrem, 500 mrem, and 5,000 mrem respectively based on EPA 400 guidance. GOJ guidance assumes an overall dose reduction of 40% for remaining indoors 16 hours per day, 0.4 attenuation factor, and 8 hours per day outdoors. Thus, the dose limits and DRL's adjustments are reflected above per GOJ guidance.

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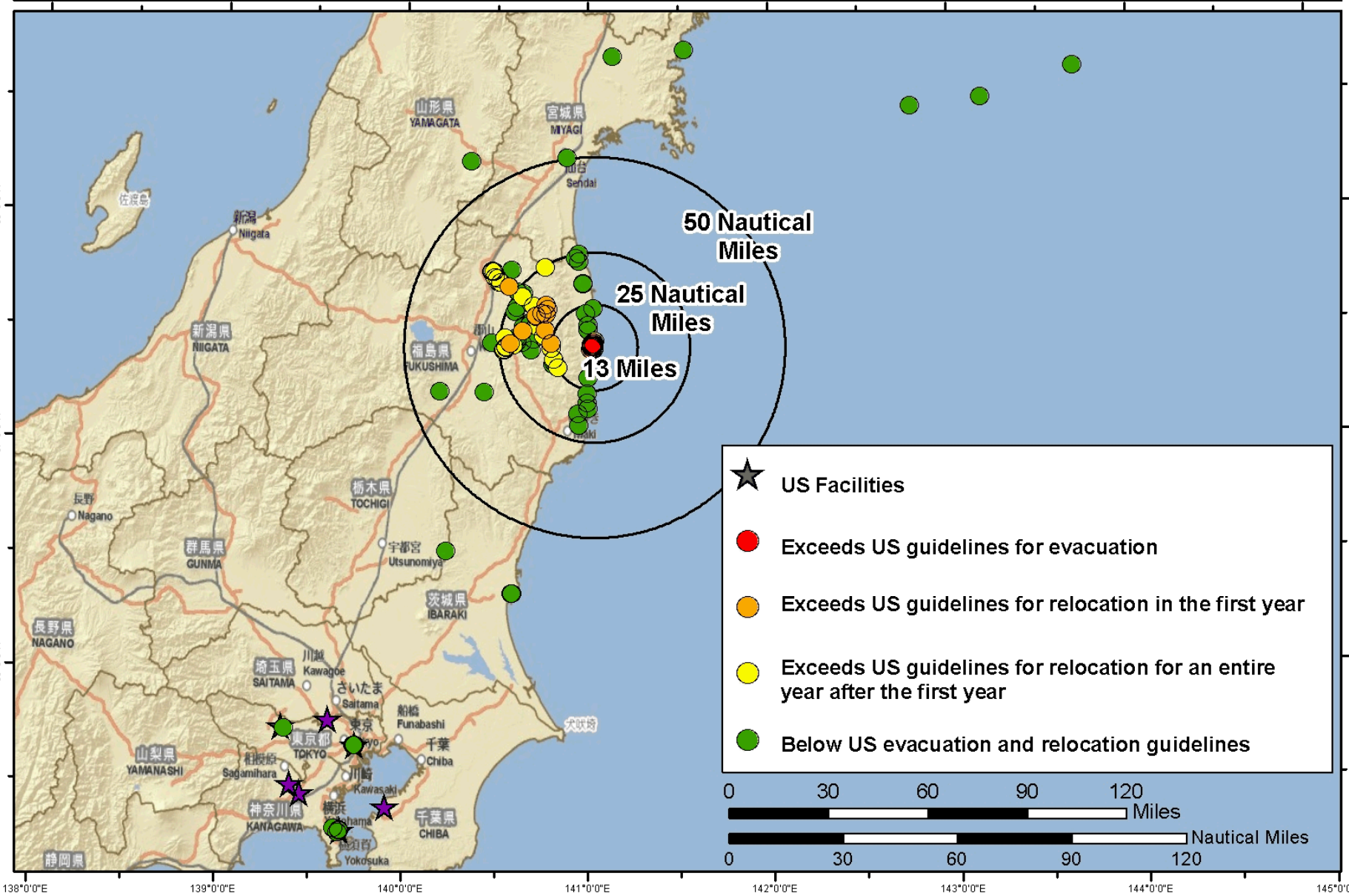
National Nuclear Security Administration

Field Monitoring Results

Data From All Sources- 2935 Points

FUKUSHIMA DAIICHI
JAPAN



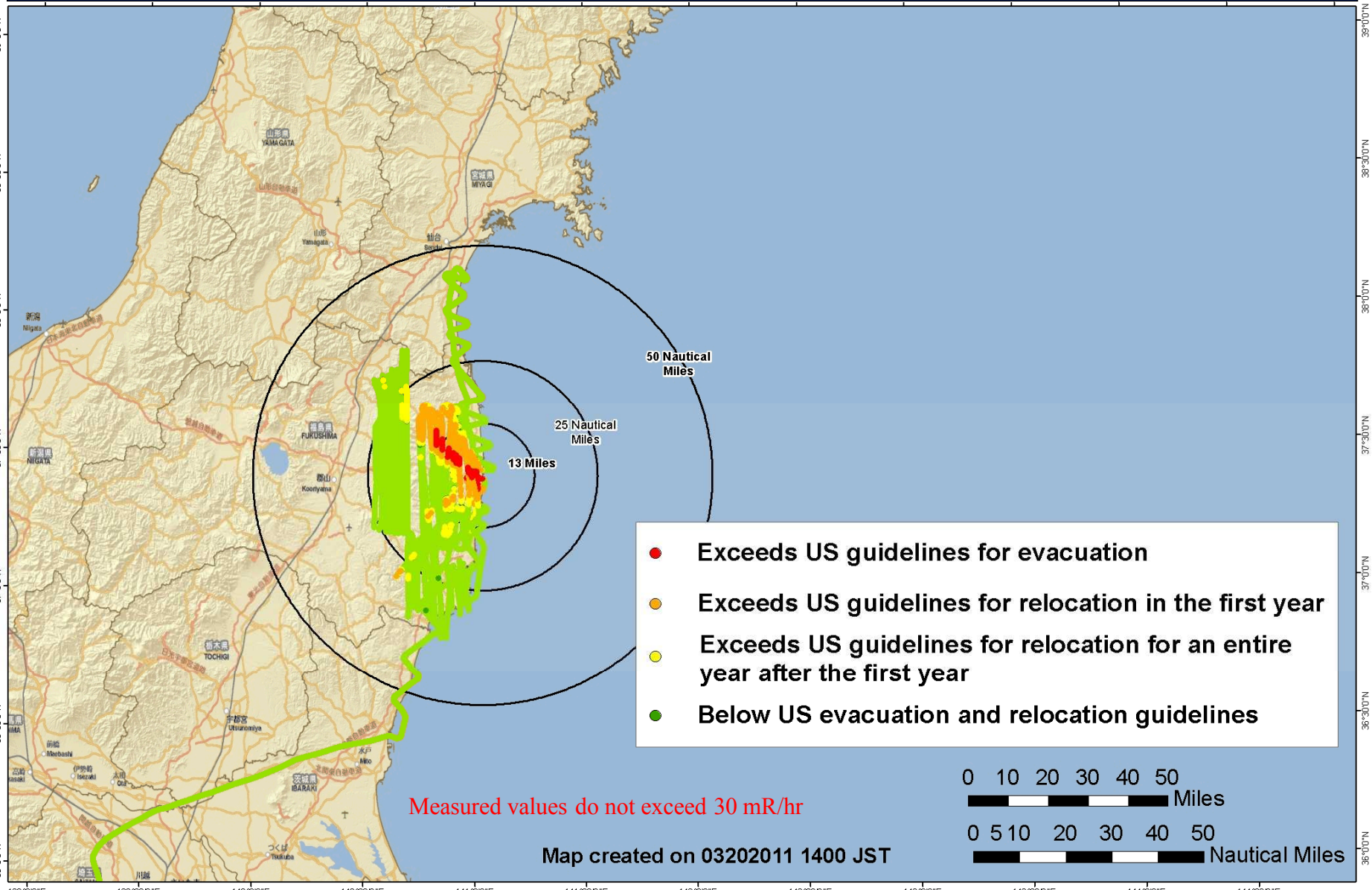
Map created on 03212011 0340 JST

Nuclear Incident Team DOE NIT
Contact (202) 586 - 8100

Aerial Monitoring Results - C12

3 Days of Flights

FUKUSHIMA DAIICHI
JAPAN

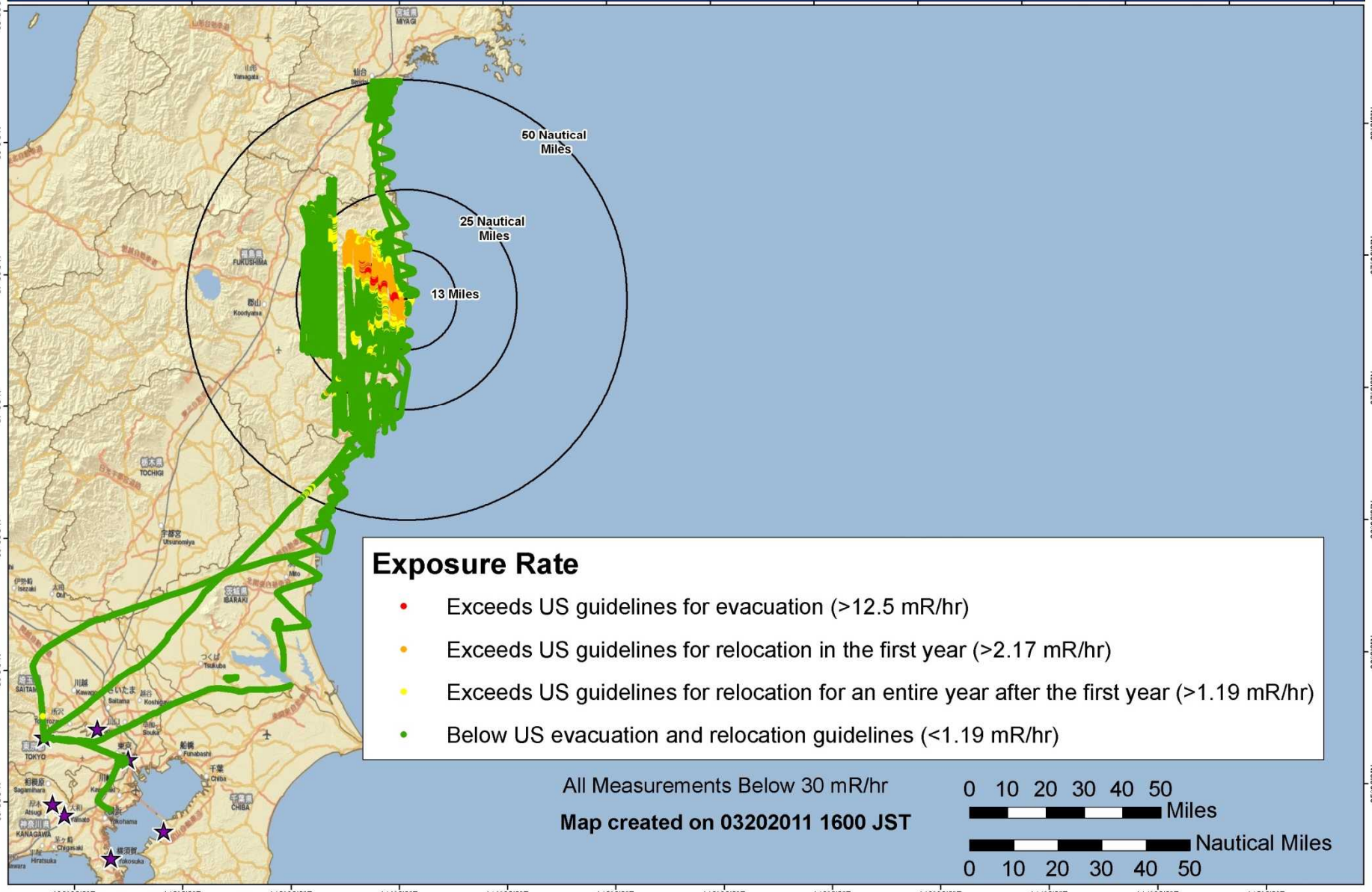


Check for revision in 12 hours

Nuclear Incident Team DOE NIT
Contact (202) 586 - 8100

Aerial Monitoring Results
Cumulative

FUKUSHIMA DAIICHI
JAPAN



Exposure Rate

- Exceeds US guidelines for evacuation (>12.5 mR/hr)
- Exceeds US guidelines for relocation in the first year (>2.17 mR/hr)
- Exceeds US guidelines for relocation for an entire year after the first year (>1.19 mR/hr)
- Below US evacuation and relocation guidelines (<1.19 mR/hr)

All Measurements Below 30 mR/hr

Map created on 03202011 1600 JST

0 10 20 30 40 50
Miles

Nautical Miles
0 10 20 30 40 50

Check for revision in 12 hours

Nuclear Incident Team DOE NIT
Contact (202) 586 - 8100

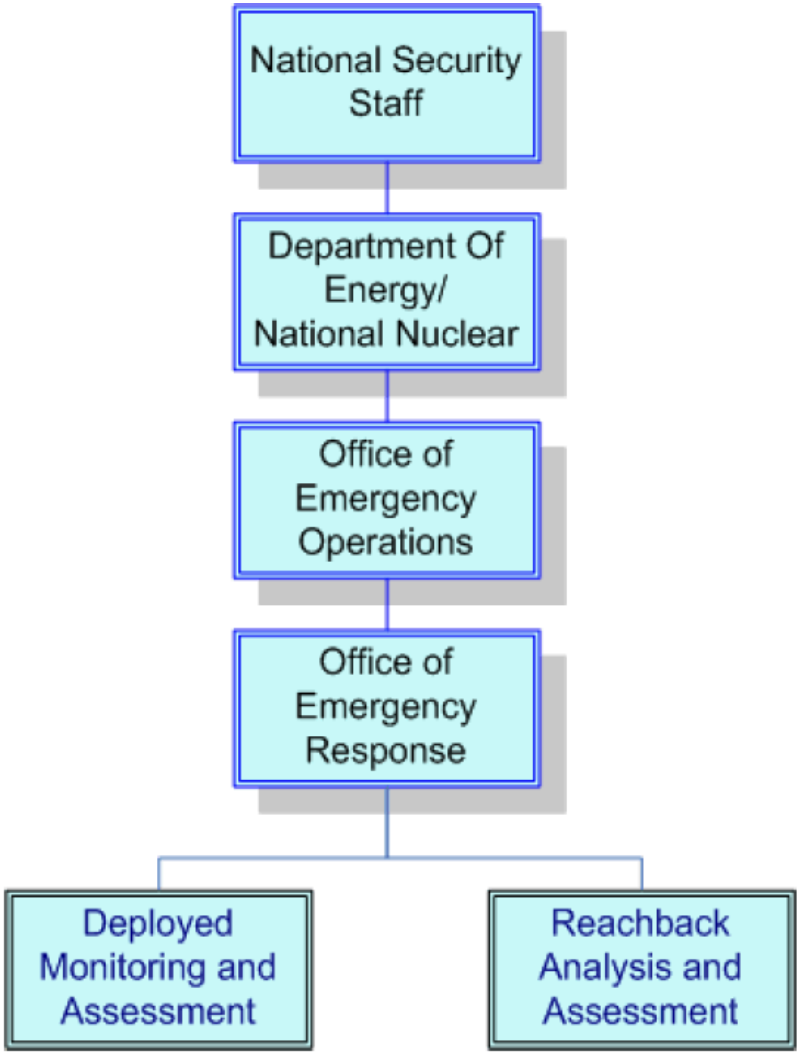
Interesting Developments

- The CM Assets reacted and responded within hours of recognizing that a reactor was in trouble.
- Japan was not requesting US response assets.
  - We are there supporting US interests.
- NRC did not seem to engage aggressively until 4 or 5 days into the event.
  - NRC's Emergency Planning elements have been very reluctant to engage with NRC R&D elements.
  - SNL does work for the NRC R&D elements and have studied these exact events, but NRC seems hesitant to use that information since it has not been through a complete review.
- Some SNL organizations with key resources were reluctant to offer them based upon the impact to their responsibilities.
  - Jill helped solve some of this, using her name solved others.

DOE Support of Operation Tomodachi

Mission:

Assess the consequences of releases from the Fukushima Dai-ichi Nuclear Power Plant (FDNPP)



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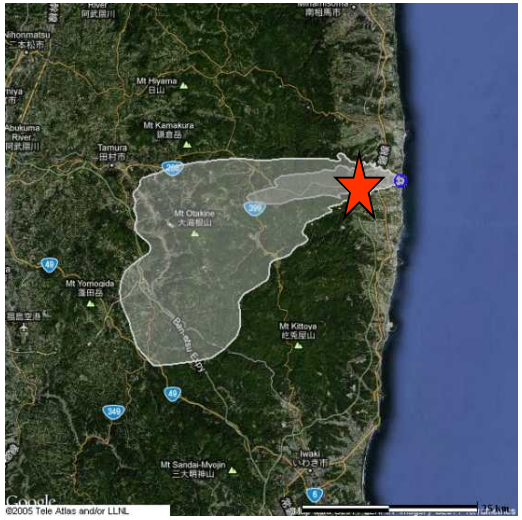
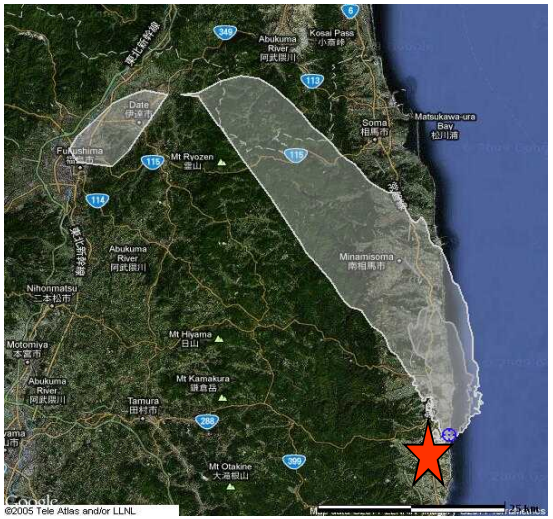
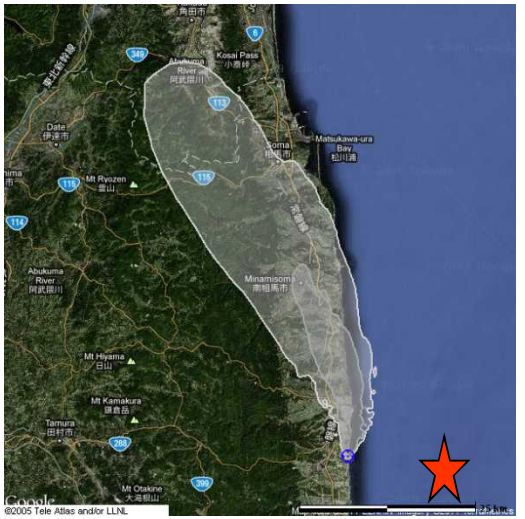
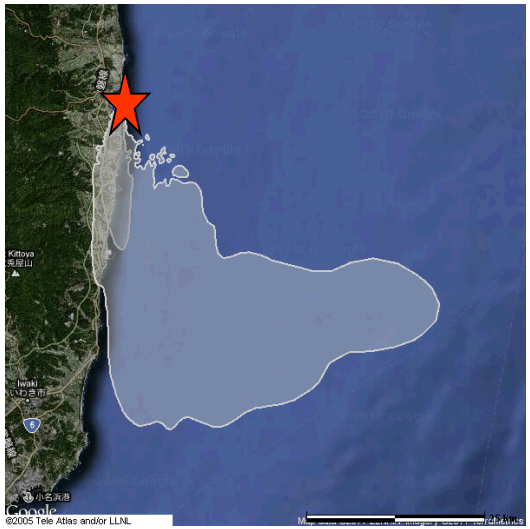
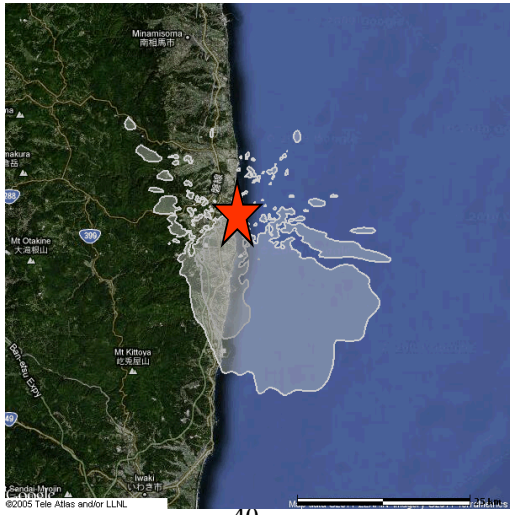
Complication of Weather Hypothetical Behavior During One Day

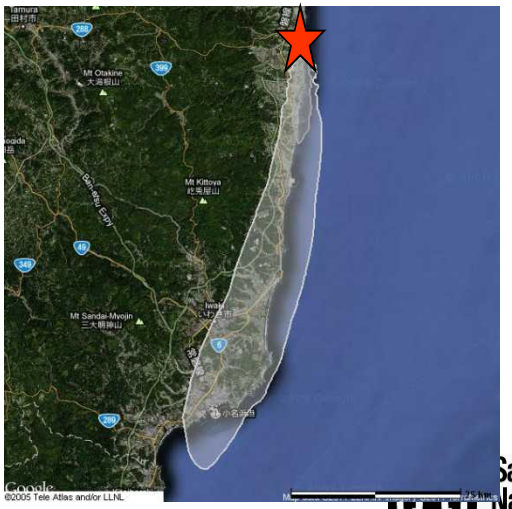












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