本スライドおよびに訳について

カルテック日本人コミュニティーでは福島原発事故への関心の高さを受け、原発事故に関する学内向け講演会を4月9日に企画実行しました。講演者は、爆発現象の専門家であり、スリーマイル島事故以来、原子力発電所の安全についても研究を行っているJoe Shepherd教授です。1時間以上に渡る講演の中で、1）原子力発電所の仕組みおよびに冷却システム、2）地震によって何がおこったかについて、詳しく解説が行われました。学内向けの講演であることから専門的ではあるものの、今回の事故を正しく理解するため、また今後の原子力発電をどうするか考えるためにも、非常に参考になる講演でした。そこでShepherd教授の許可のもと、以下の情報を公開しました。

1）講演を撮影した動画の公開（英語）
2）講演スライドの公開（英語）
3）講演スライドのタイトルの日本語訳（本pdf）
（リンク：http://www.galcit.caltech.edu/~jeshep/fukushima/）

これらの資料が皆様のお役に立てば幸いです。

なお、放射性物質やその安全性については本講演の主目的ではなかったため、ほとんど触れられていません。それらの内容については既に詳しいサイトがありますのでそちらをご参照ください（例：http://ribf.riken.jp/%7Ekoji/jishin/zhen_zai.html）。

またカルテック日本人コミュニティーでは本講演以外にも、被災地支援のため学内にて募金活動を行いました。小さい大学ながらも多くの方から総額$14,000以上の寄付、そして多くの心配と温かい言葉、復興への祈りを受け取りました。微力ながらも被災した方々の助けになるよう、共同基金の義援金として全額寄付しました。被災地の一日でも早い復興をお祈り申し上げます。

カルテック日本人コミュニティー有志

The Crisis at Fukushima Dai-ichi Nuclear Power Plant

Prof. Joseph E Shepherd
Aerospace and Mechanical Engineering
California Institute of Technology
Pasadena, CA

April 2011

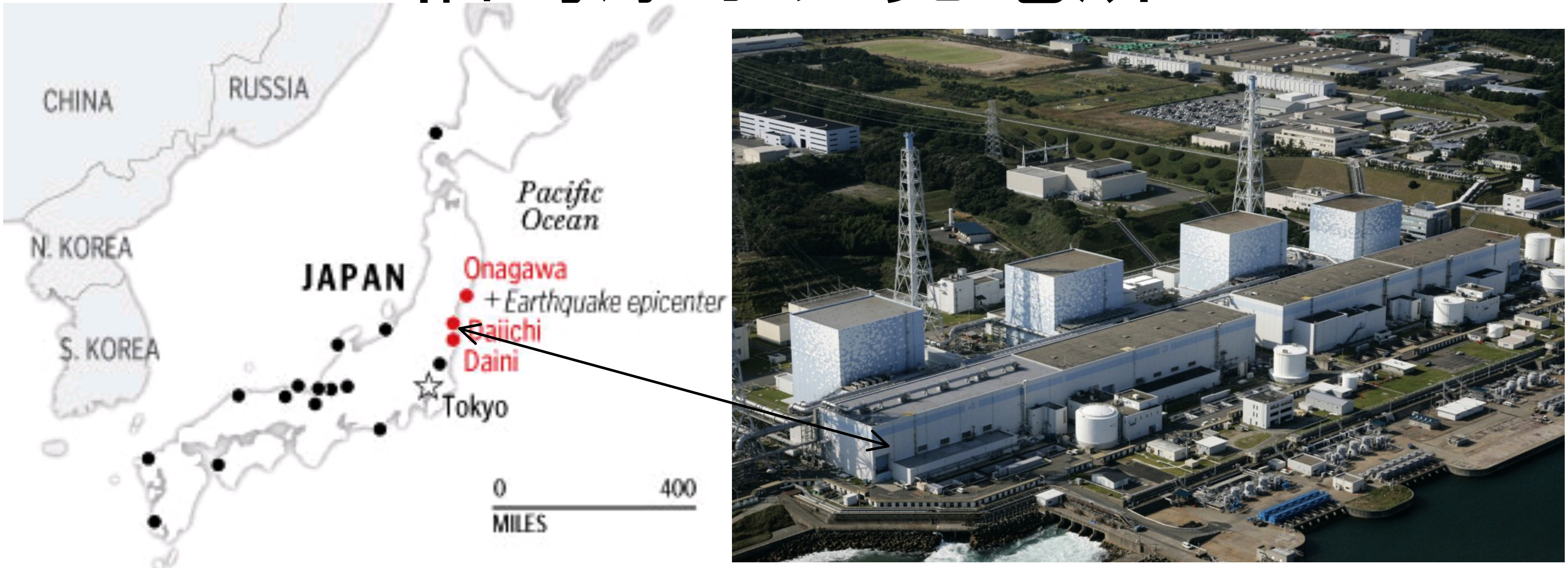
東北大震災による、福島第一原発での危機は、かつてないほどの非常事態を招いております。あまりにも大規模な事故のため情報が入れ乱れており、私が知らないことも多くあると思われます。また、私が耳にする情報にも誤ったものが含まれている可能性があることを理解した上で、このプレゼンテーションをご覧ください。
事故の進行状況とは、事故の第一印象から受けるイメージとかけ離れている場合が多く、事後分析によって始めて明らかにされることも多くあります。今後の分析によって今回の事故の行程が、現在の評価から大きく異なってくる可能性もあることを理解ください。
このプレゼンテーションは福島第一原発の原子炉についての予備知識、事故の経過のまとめ、さらには私が持つ情報を下に私が抱く事故の見解、を皆さんに提供することを目的としています。私の目標は原子力を専門としない人に、現在メディアによって伝えられている情報をより理解しやすくし、今回の事故を過去40年にわたる原子力安全研究と照らし合わせることにあります。この過程で、専門的な内容を説明しやすくするために、プレゼンテーション内で施設の概略図や数値の四捨五入等、簡略化してある場所がところどころあります。より具体的な情報はスライドに掲載してある参考文献にて調べることが可能です。

最後に東北大震災で被災した方やその後家族の方にお悔やみ申し上げます。また少しでも貢献できる機会を与えてくださったカルテックの日本人コミュニティにも感謝の意を申し上げます。

Joe Shepherd
Pasadena, CA
9 April 2011

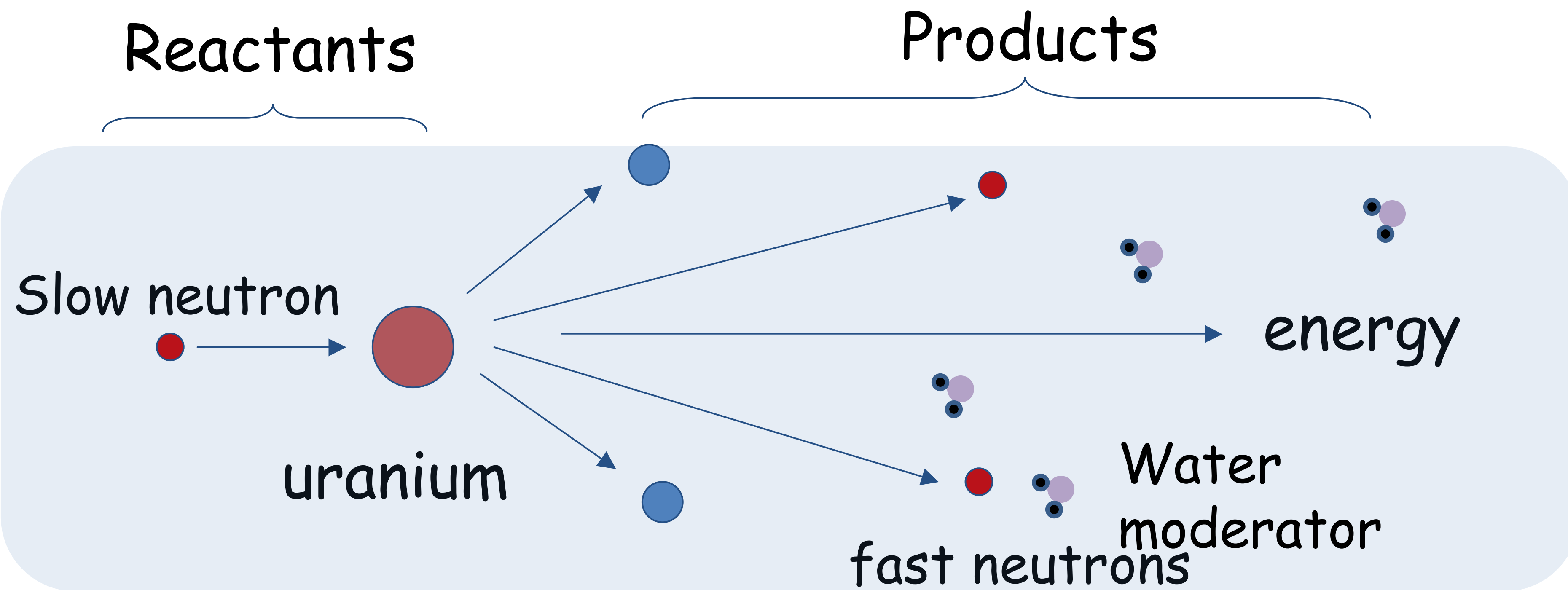
http://www.galcit.caltech.edu/~jeshep/fukushima/

福島原子力発電所



- Fukushima-Daiichi 1, 2, 6 made by GE, rated at 439, 760, 1067 MWe, started up in Nov. 1970, Dec. 1973, May 1979
- Fukushima-Daiichi 3 and 5 made by Toshiba, rated at 760 MWe, started up in Oct. 1974 and September 1977
- Fukushima-Daiichi 4 made by Hitachi, rated at 760 MWe, started up in Feb 1978.
- Fukushima-Daini 1 and 3 made by Toshiba, rated at 1067 MWe, started up in July 1981 and Dec. 1984.
- Fukushima-Daini 2 and 4 made by Hitachi, rated at 1067 MWe, started up in June 1983 and Dec. 1986.

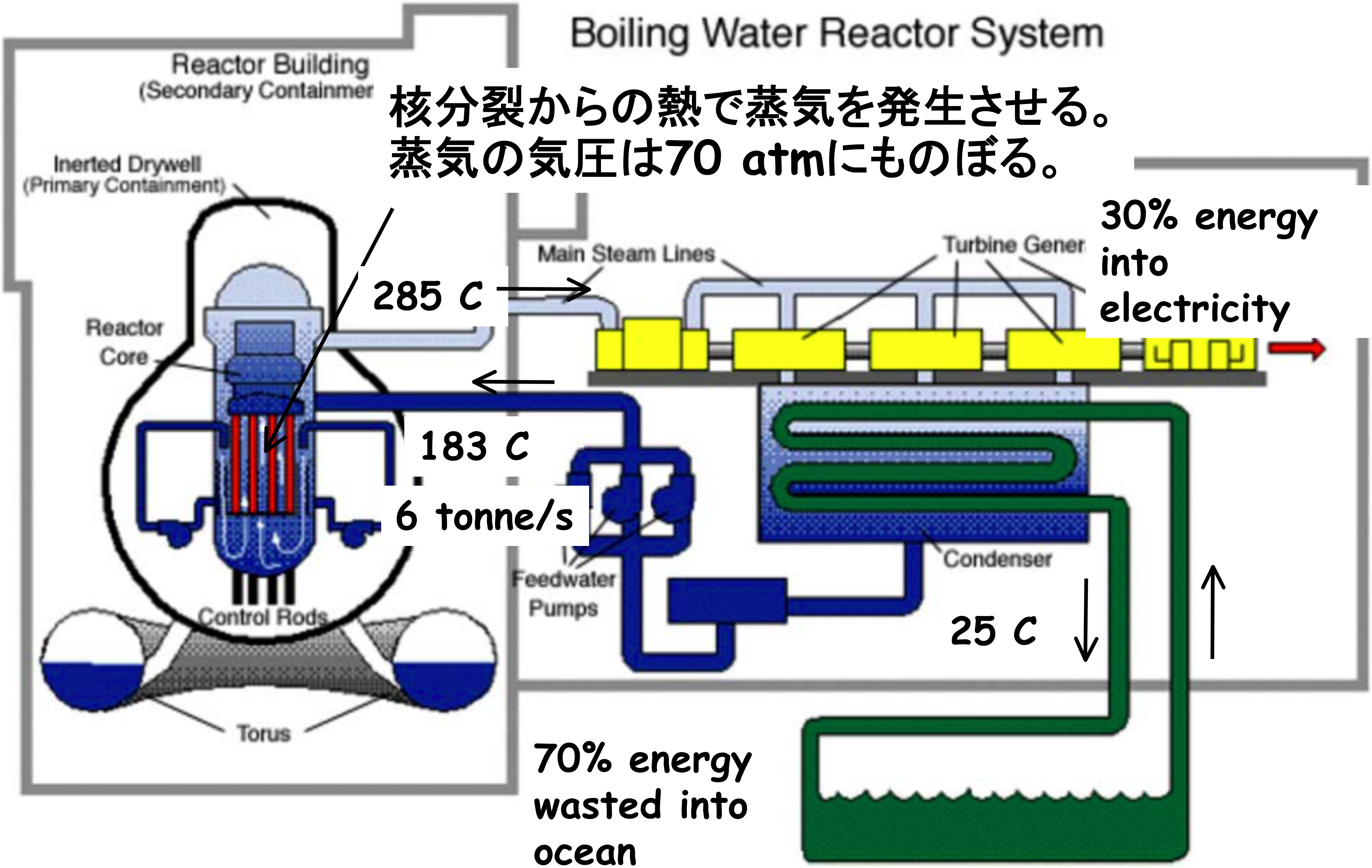
原子炉内で起こる核分裂



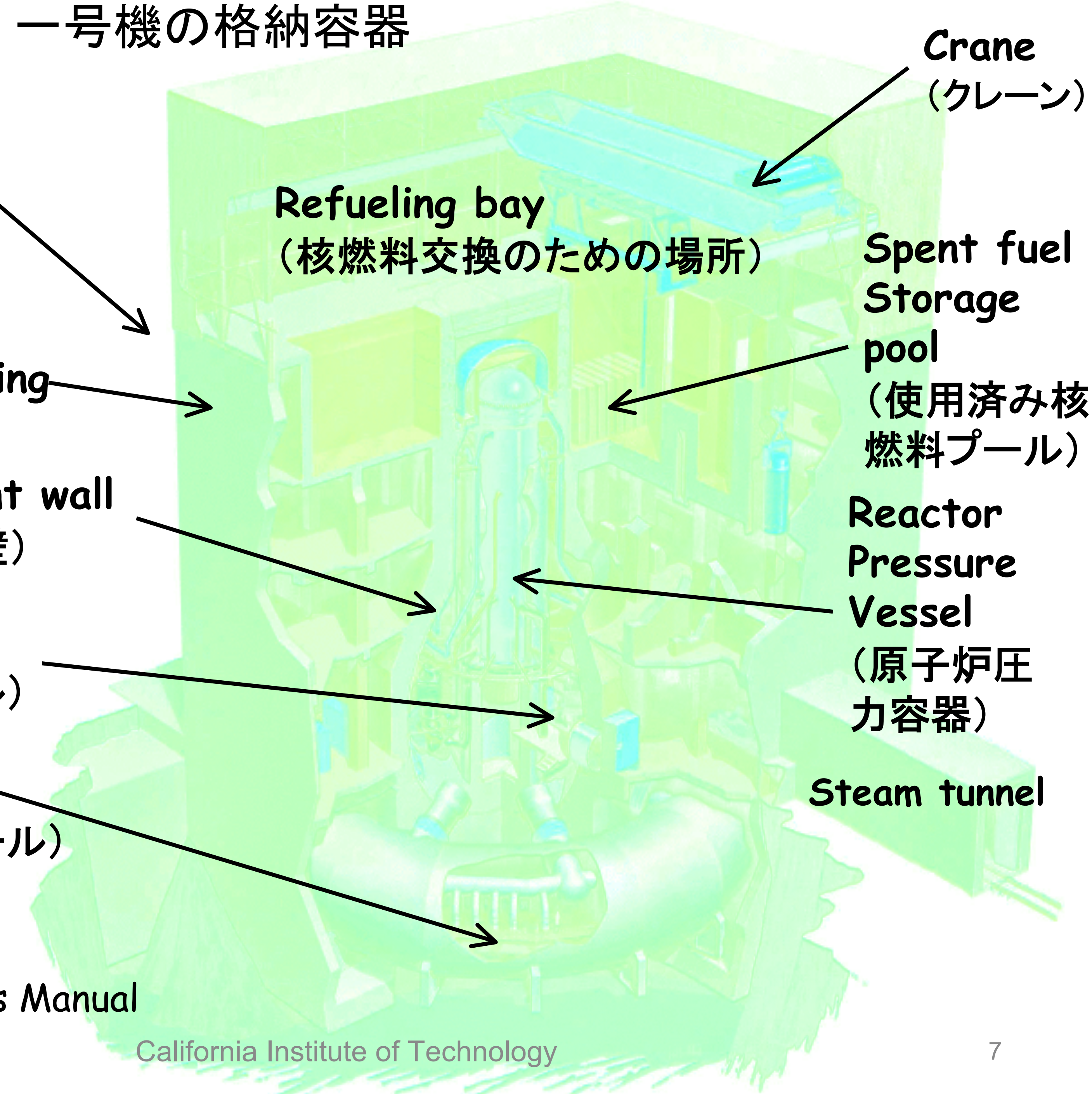
n + ^{235}U ⟶ 2.5n + products + 200 MeV

1トンの^{235}U から、一年に 1 GW(e) のエネルギーが得られる（32% の熱変換効率）。燃料は ^{235}U (3%) と ^{238}U (97%) の混合物 - 33 tonne fuel per GW-yr of electricity.

沸騰水型原子炉の概略図

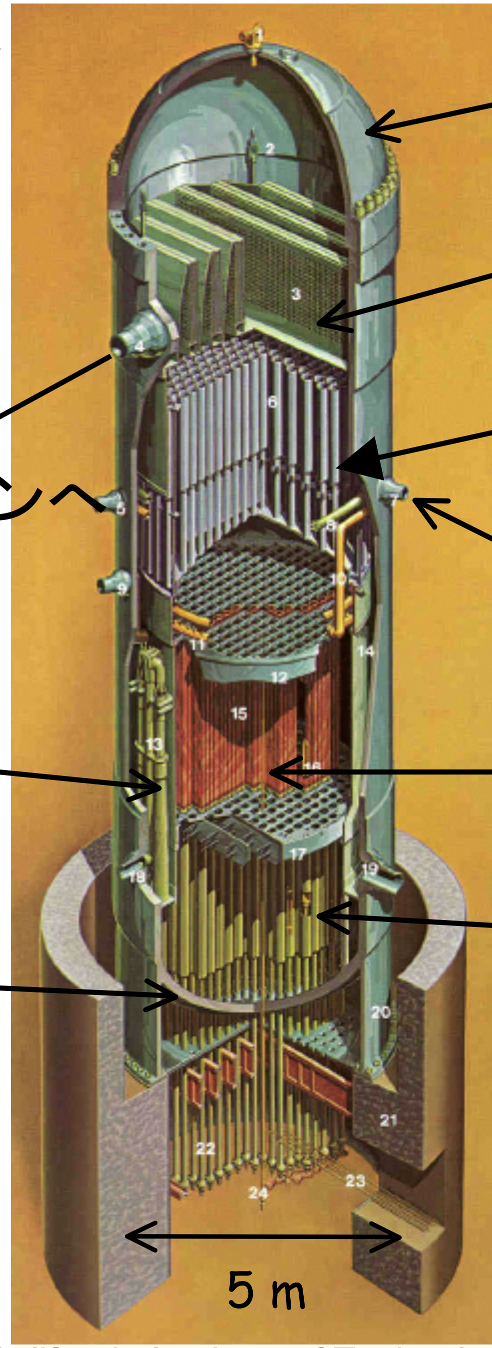


一号機の格納容器



NRC Reactor Concepts Manual

原子炉圧力容器と核燃料



500トン、6インチのスチール

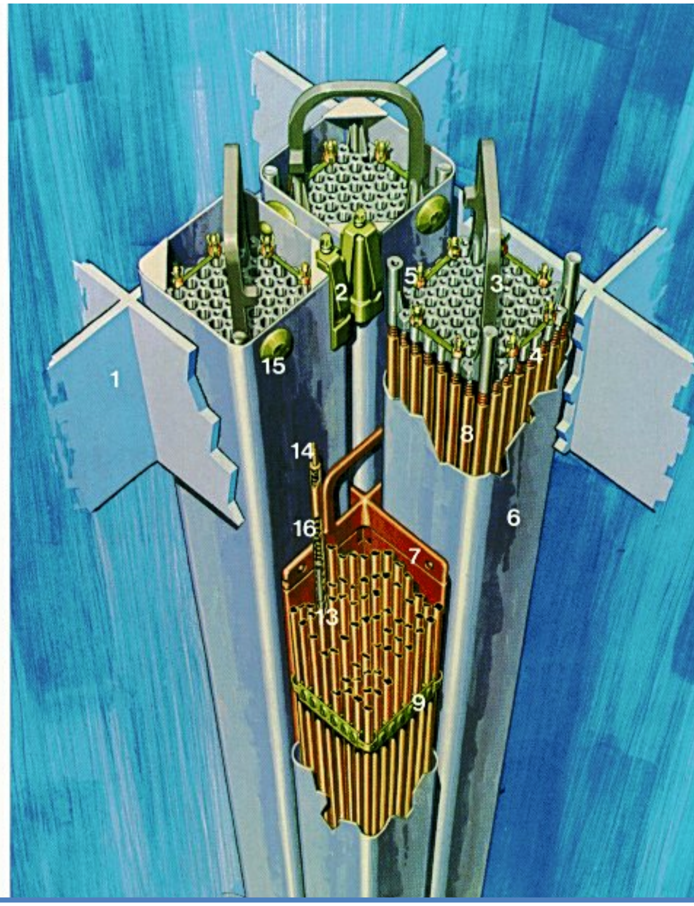
NRC Reactor Concepts Manual

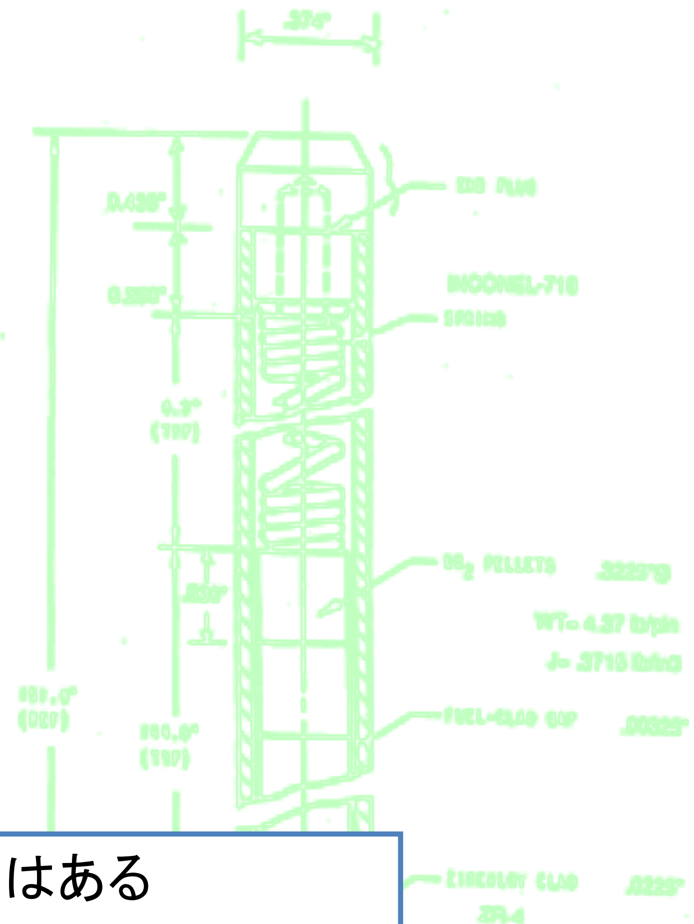
代表的な核燃料の集合体図

Each 8x8 set of pins are surrounded by Zircaloy channel boxes.

There is one common cruciform control blade for the set.

Cores in units 2 and 3 are larger than 1.





- 94 (68) トンのウランが炉心にはある
  - 548 (400)の核燃料集合体
  - それぞれ63 の核燃料棒(8 x 8 array)
  - 137 (97) の制御ブレード(炭化ホウ素)

一次格納容器

Dry well
(ドライウェル)

Wet well

許容圧力:
デザイン 4 atm
限界　8 atm
破損　10 atm?

Inverted light bulb,
contains reactor
pressure vessel,
Body: 33 m high
11 m diameter
Sphere: 20 m diam.

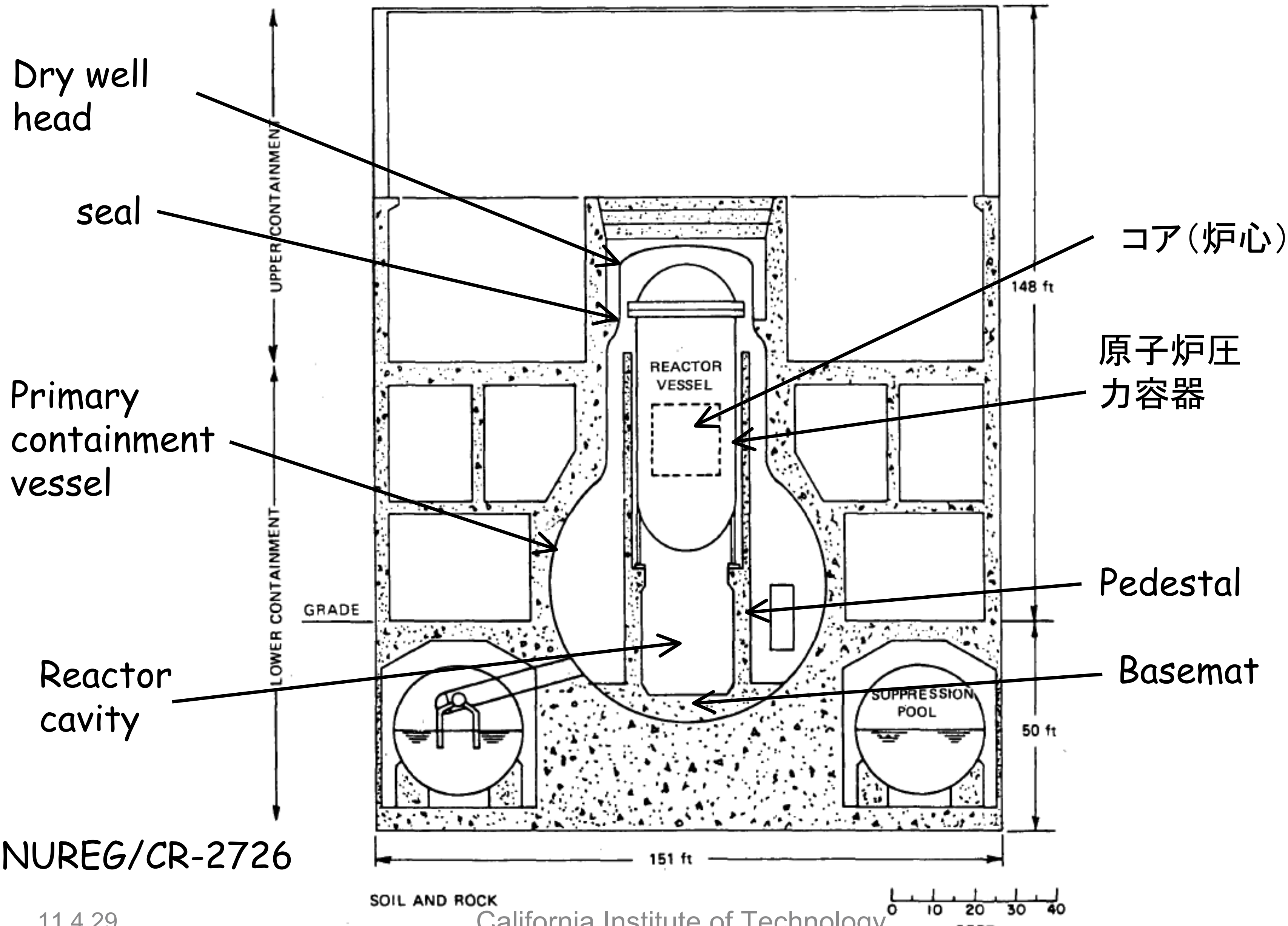
Vent pipes

サプレッションプールのある円環部(トーラス)

一次格納容器の蓋

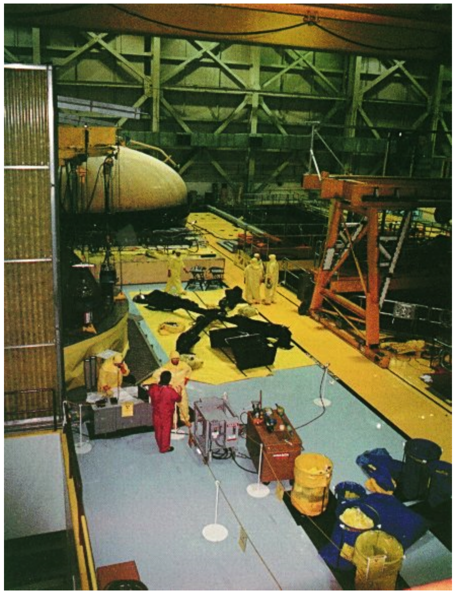
Brown's Ferry

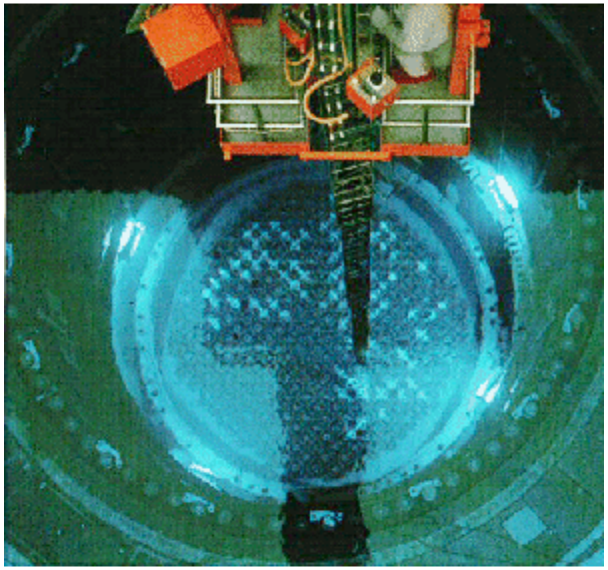
一号機の格納容器の概略図



NUREG/CR-2726

燃料補給—12ヶ月～15ヶ月間に三分の一が交換される





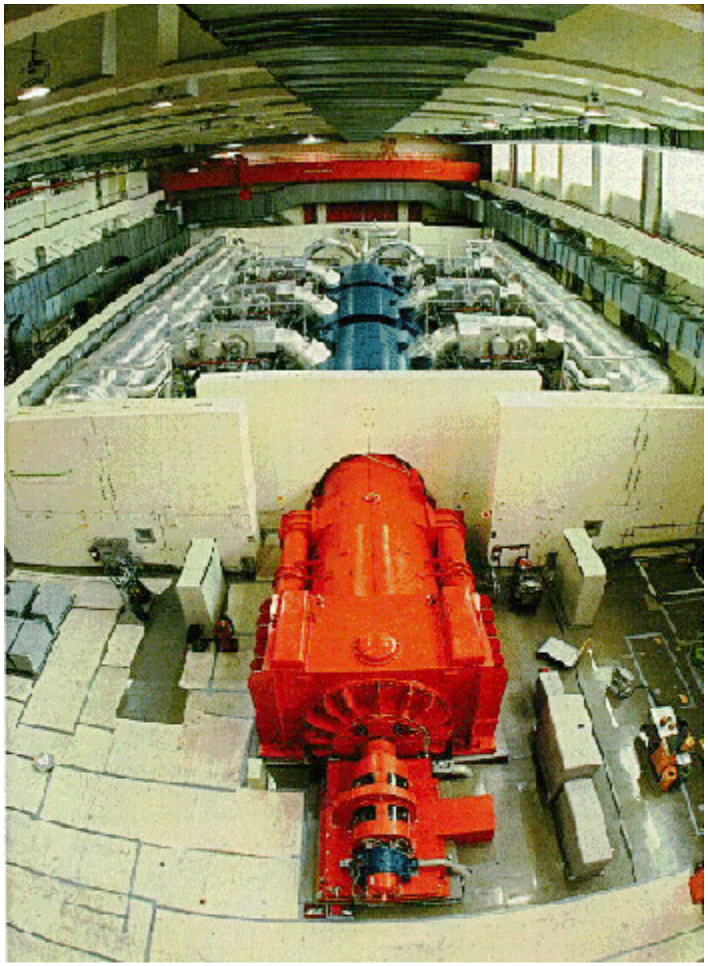
Primary containment and reactor pressure vessel heads are removed

Blue glow is Cerenkov radiation – water serves as “biological shield”

Fuel assembly is being handled with operators standing on the platform

http://www.nucleartourist.com/

タービンと発電機

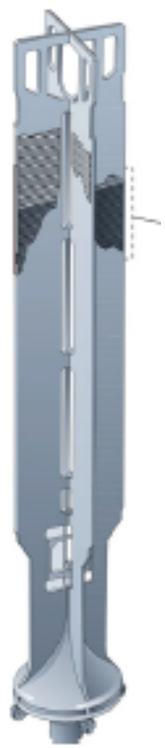


Turbine surrounding by shielding to protect operators.

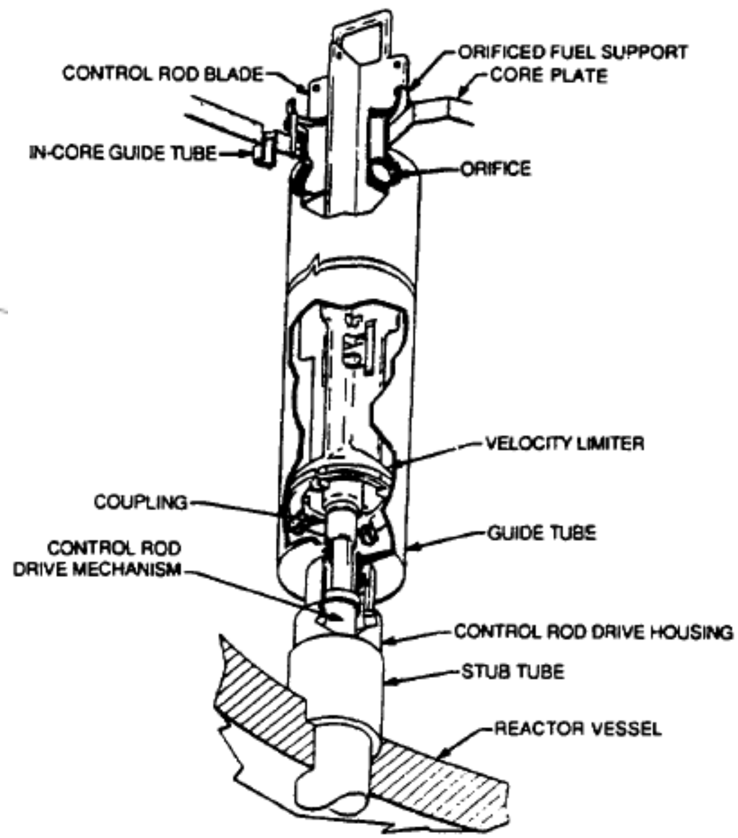
Water passing through reactor picks up radionuclides that are released from fuel pins through defects or diffusion. Impurities in water are activated. Radiolysis generates H2 and O2 in water

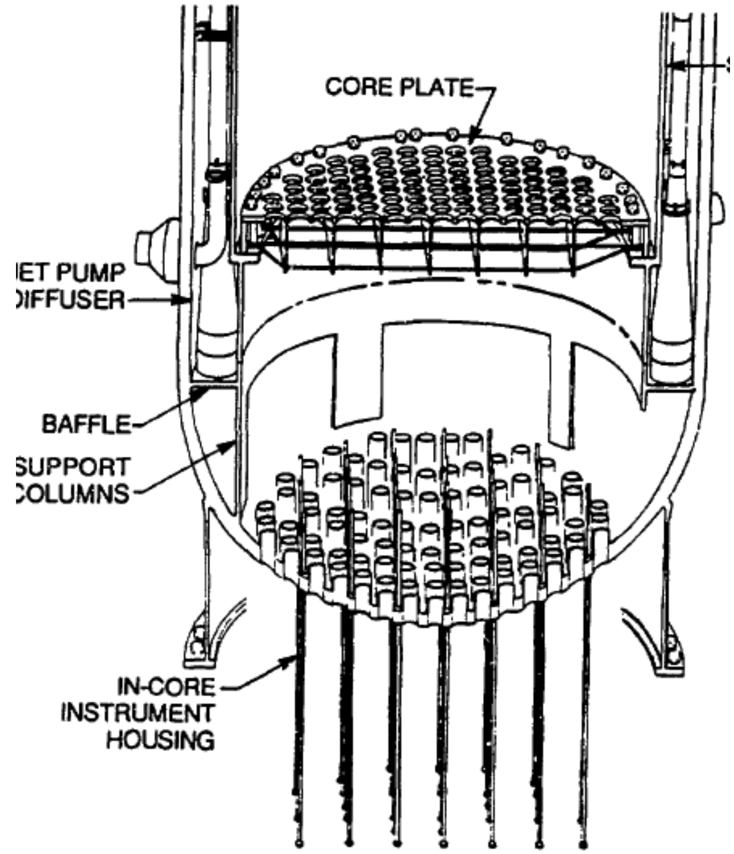
http://www.nucleartourist.com/

制御棒システム

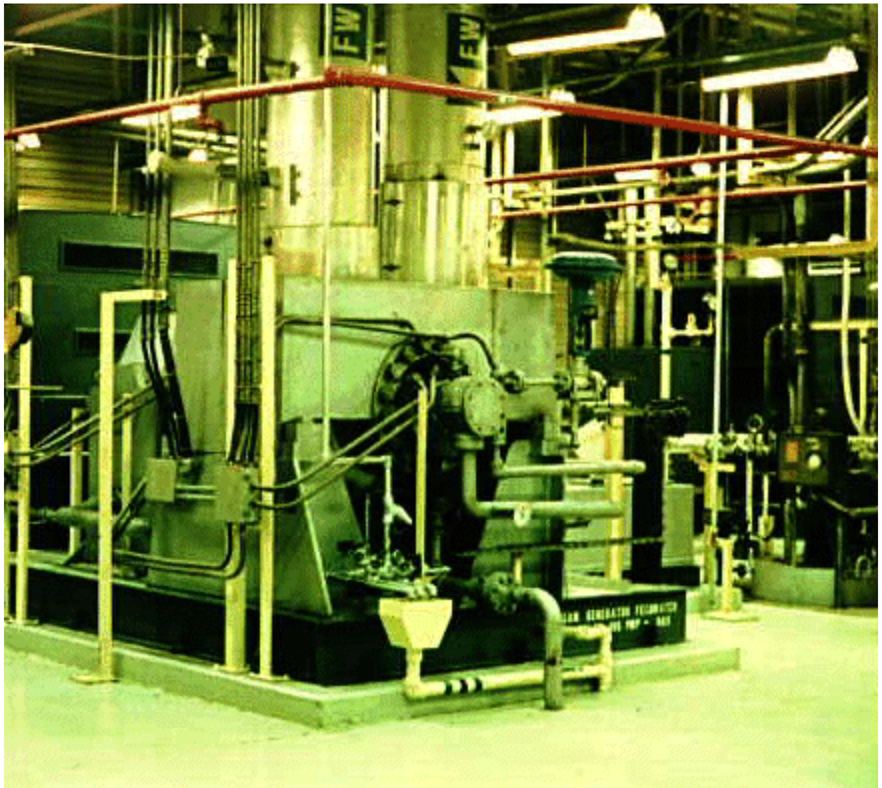


Westinghouse BWR control rod CR 82M-1





蒸気駆動型給水ポンプ

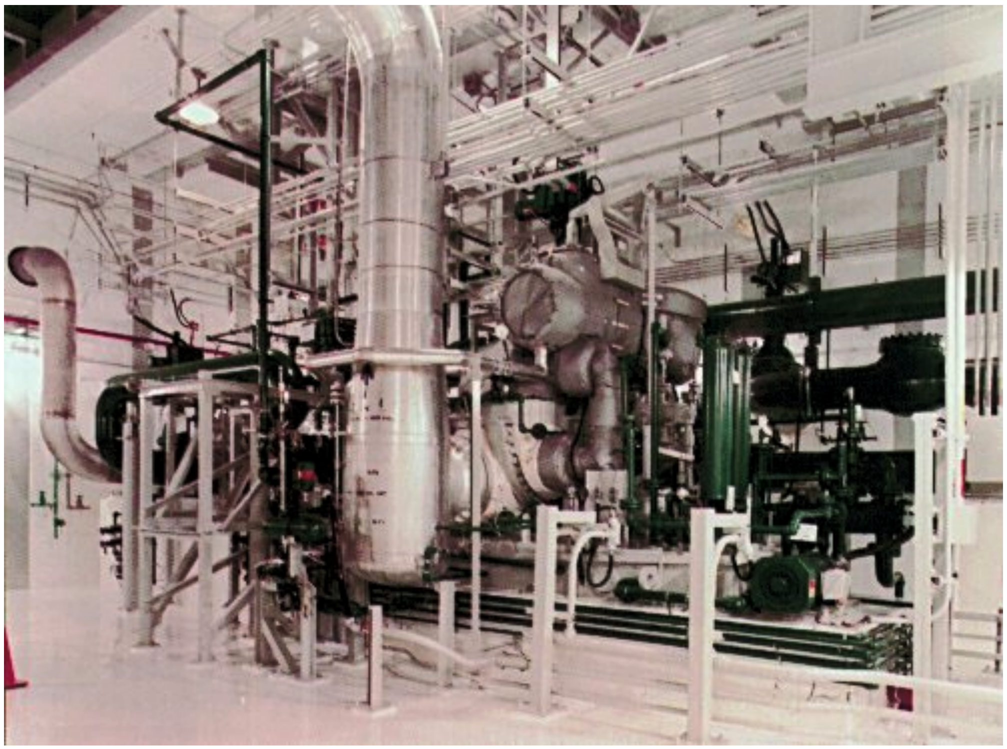


600 gpm, 150-1000 psi

138 t/h 1- 6.8 MPa

http://www.nucleartourist.com/

高圧力冷却水放出ポンプ

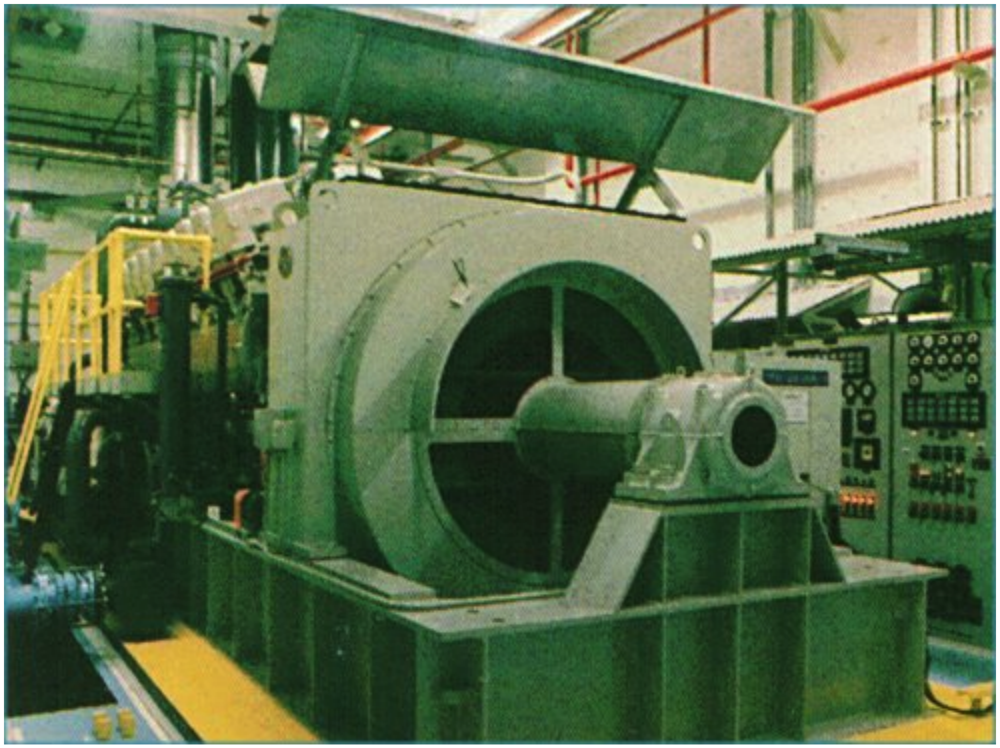


5000 gpm @ 150 to 1000 psig

1134 t/h　1 to 6.8 MPa

http://www.nucleartourist.com/

緊急ディーゼル発電機



Typical installation is 2 - 6 MWe per generator set.

Usually at least 2 per reactor unit.

http://www.nucleartourist.com/

バックアップ電力

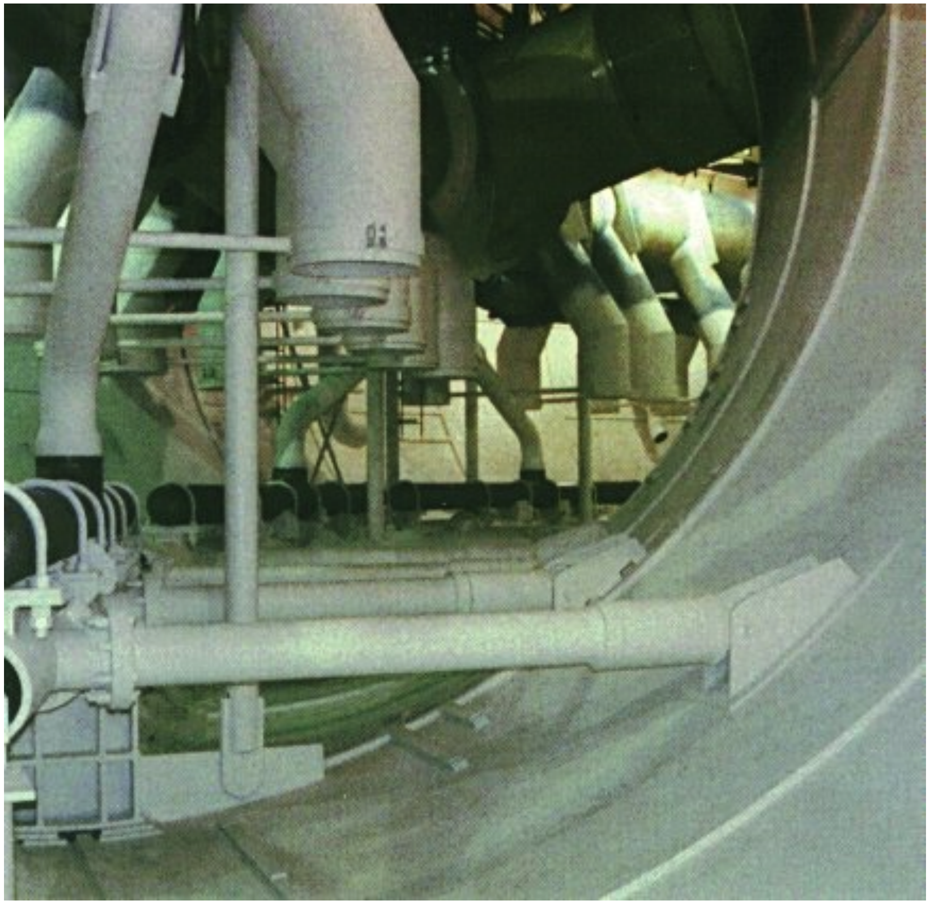
Connected to inverters to generate AC power.

Used only to power key instruments and controls.

Enough capacity for 8 hrs operation.

サプレッションプール

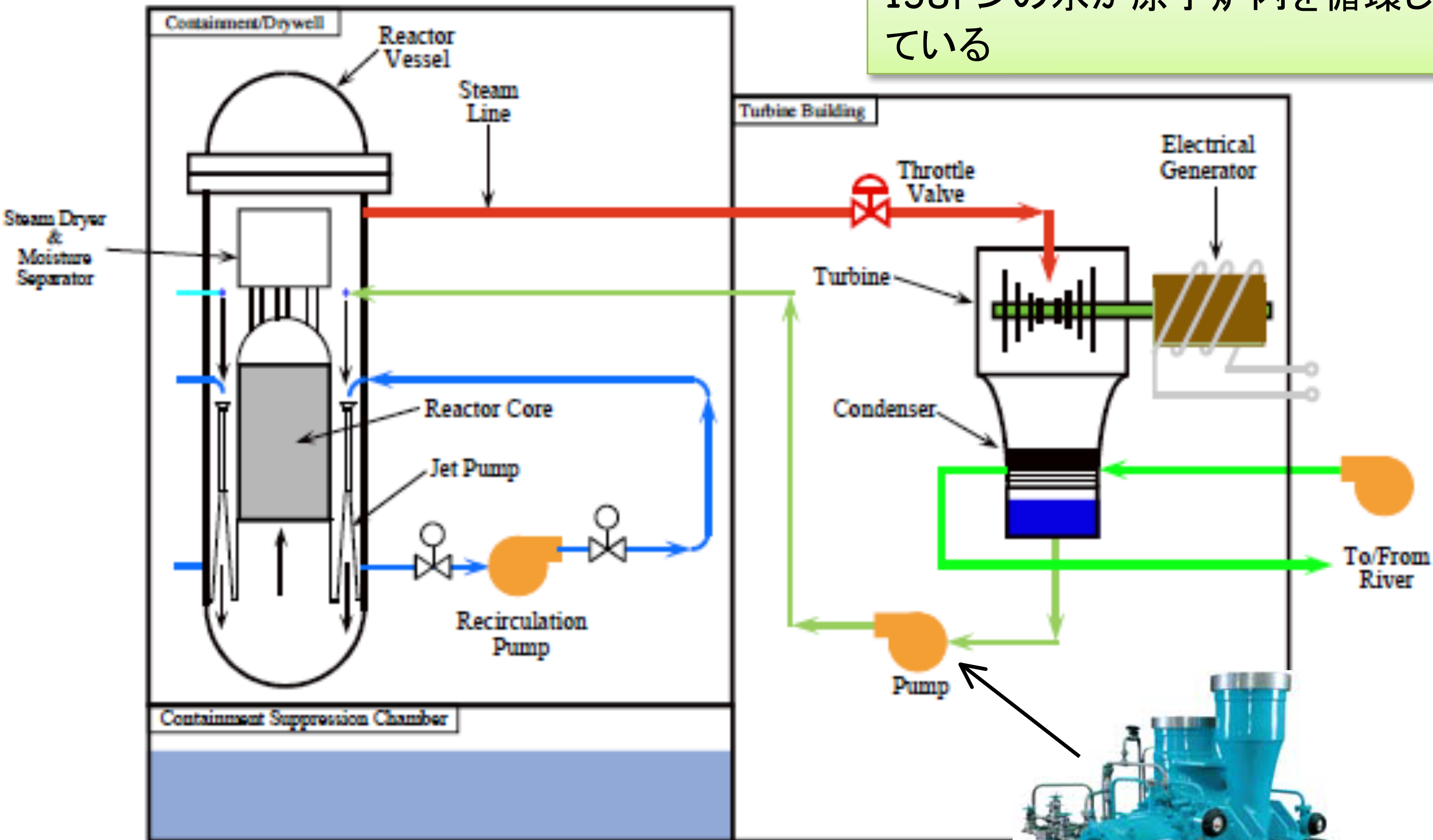
Units 2,3,4 contain 2980 tonne water (1750 for unit 1)
Connected to sphere with vent lines, vacuum breakers for reverse flow



制御室

正常駆動している時

138トンの水が原子炉内を循環している



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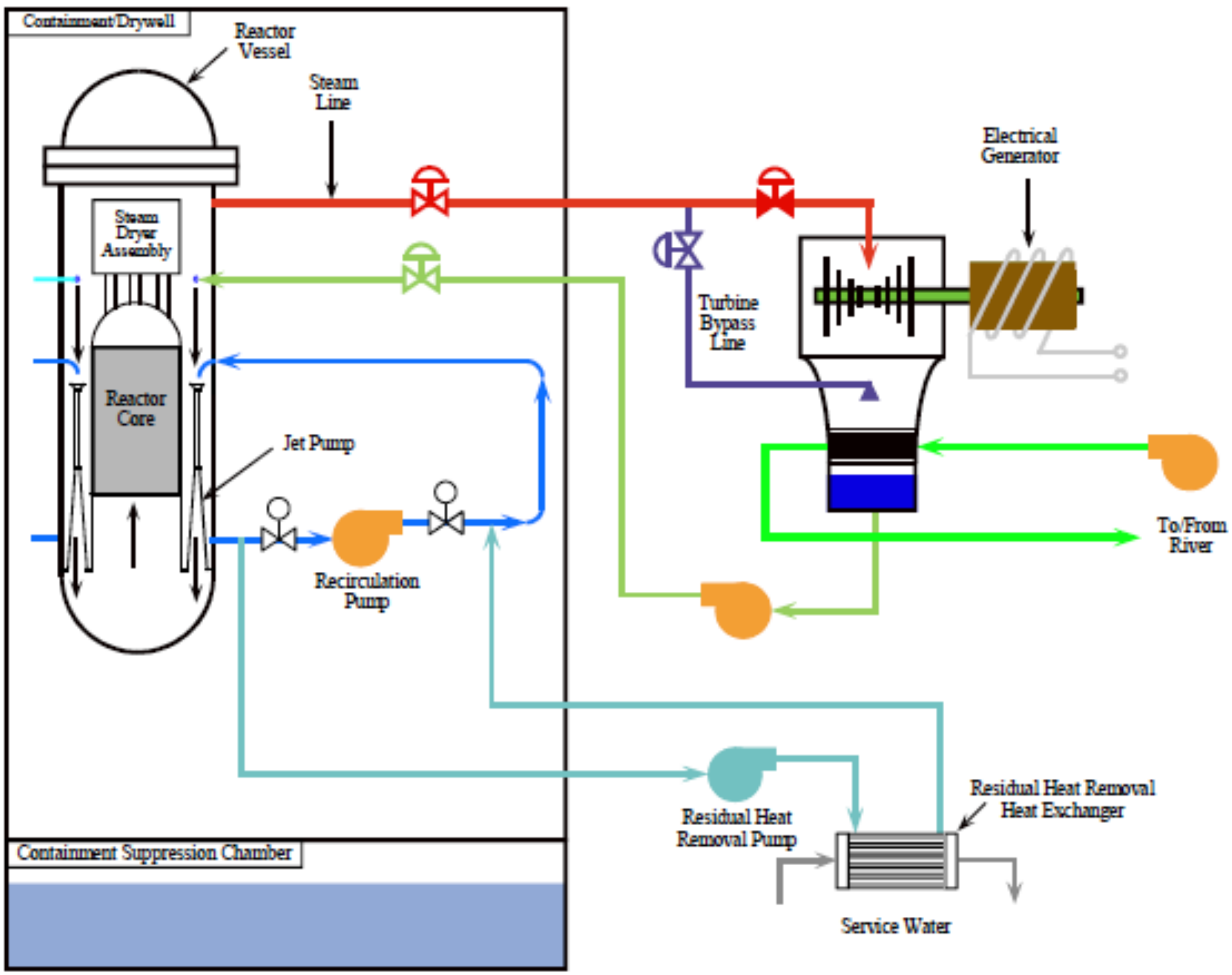
通常の原子炉停止 – 残留熱の除去



制御棒が挿入される

タービンがバイパスされる(紫の線)

ポンプによって燃料への水の循環が行われる(青の線)

崩壊熱を除去するための水の循環が行われる（淡青の線）

そして原子炉はゆっくりと冷やされ、減圧される

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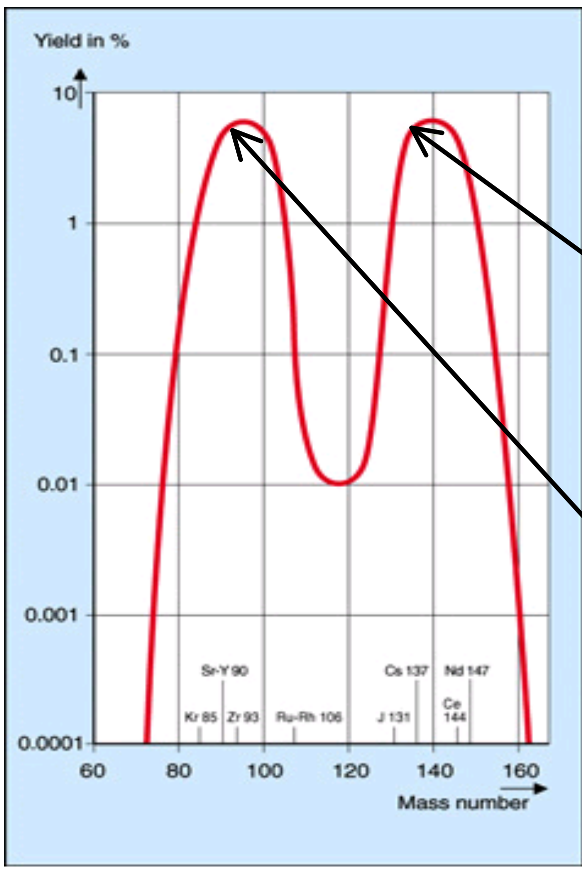
放射性物質と原発

- 1000 kg の燃料
  - 30 kg は U-235
  - 970 kg は U-238
- 3年間の原発運用の後
  - 7 kg は U-235
  - 940 kg は U-238
  - 9 kg は Pu
  - 6 kg は アクチノイド
  - 38 kg は核分裂生成物 ~100種の放射性同位体で Ce-137, I-131, Sr-90などを含む

- Multiple Barriers to release
  - Cladding on fuel rods
  - Reactor Pressure Vessel, piping, turbine, condenser
  - Primary containment vessel
  - Suppression pool
  - Reactor, turbine building at negative pressure
  - Filter ventilation and exit through stack

核分裂生成物質の崩壊

- 核分裂によって精製された放射性同位体は(中性子過多のため)不安定で放火する。その際、エネルギーを放出する。そのエネルギーが熱となって燃料へいく。
- 崩壊は自発的なものであり、止めることはできない。



Process occurs through a chain of beta decay $n \rightarrow p + e^- + \bar{\nu}$ and gamma decay $A^* \rightarrow A + \gamma$ releasing an additional ~1 Mev energy per decay.

$^{137}Te \rightarrow {}^{137}I \rightarrow {}^{137}Xe \rightarrow {}^{137}Cs \rightarrow {}^{137}Ba^* \rightarrow {}^{137}Ba$

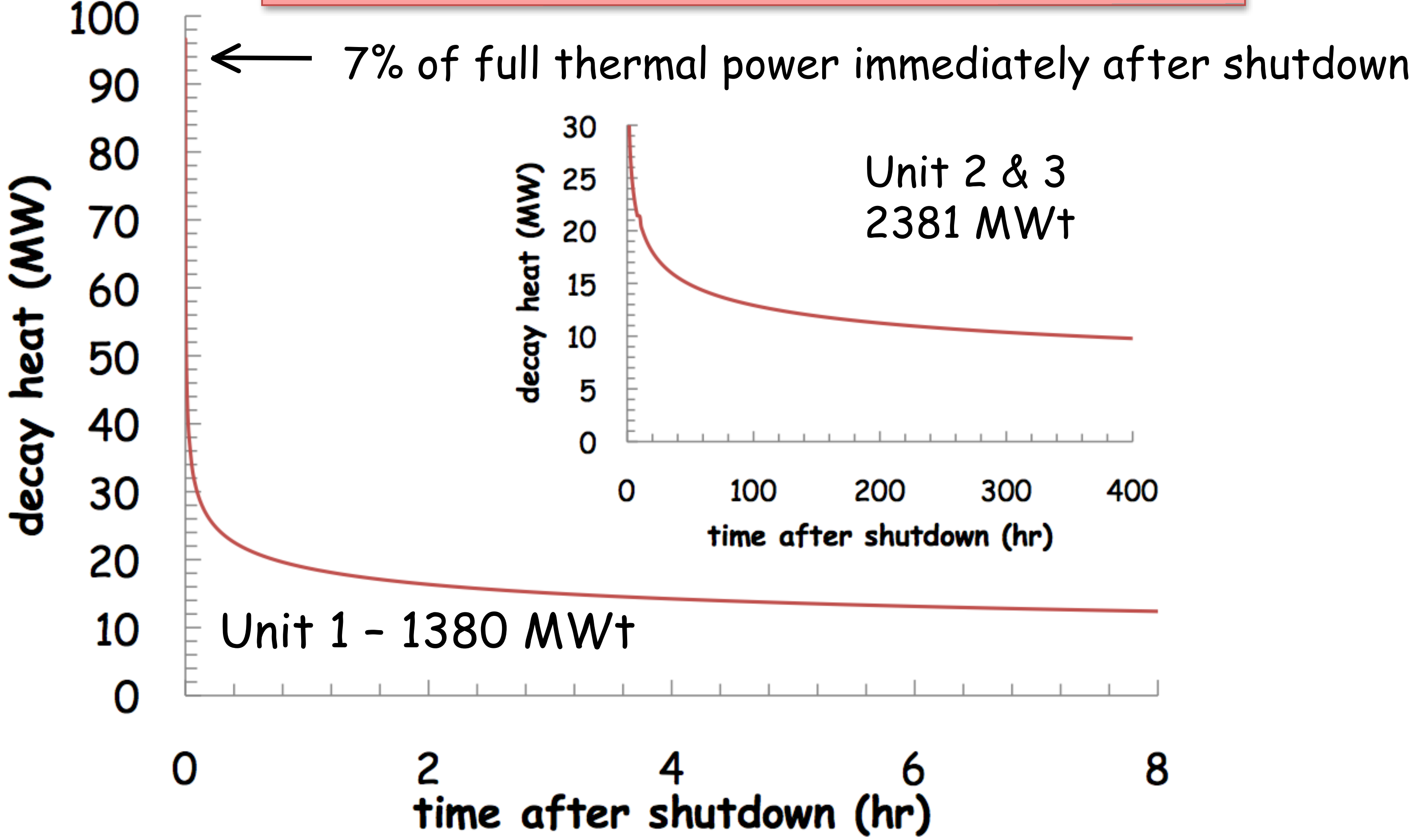
Chain terminates when a stable isotope is formed

$^{90}Kr \rightarrow {}^{90}Rb^* \rightarrow {}^{90}Rb \rightarrow {}^{90}Sr \rightarrow {}^{90}Y^* \rightarrow {}^{90}Y \rightarrow {}^{90}Zr^* \rightarrow {}^{90}Zr$

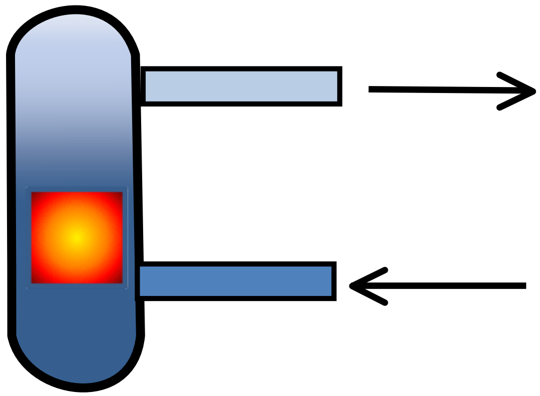
http://www.euronuclear.org/info/encyclopedia/f/fissionyield.htm

核分裂生成物は崩壊熱を生む

崩壊熱は核分裂生成物のベータ崩壊およびガンマ崩壊によって発生する



冷却水による冷却に必要なこと

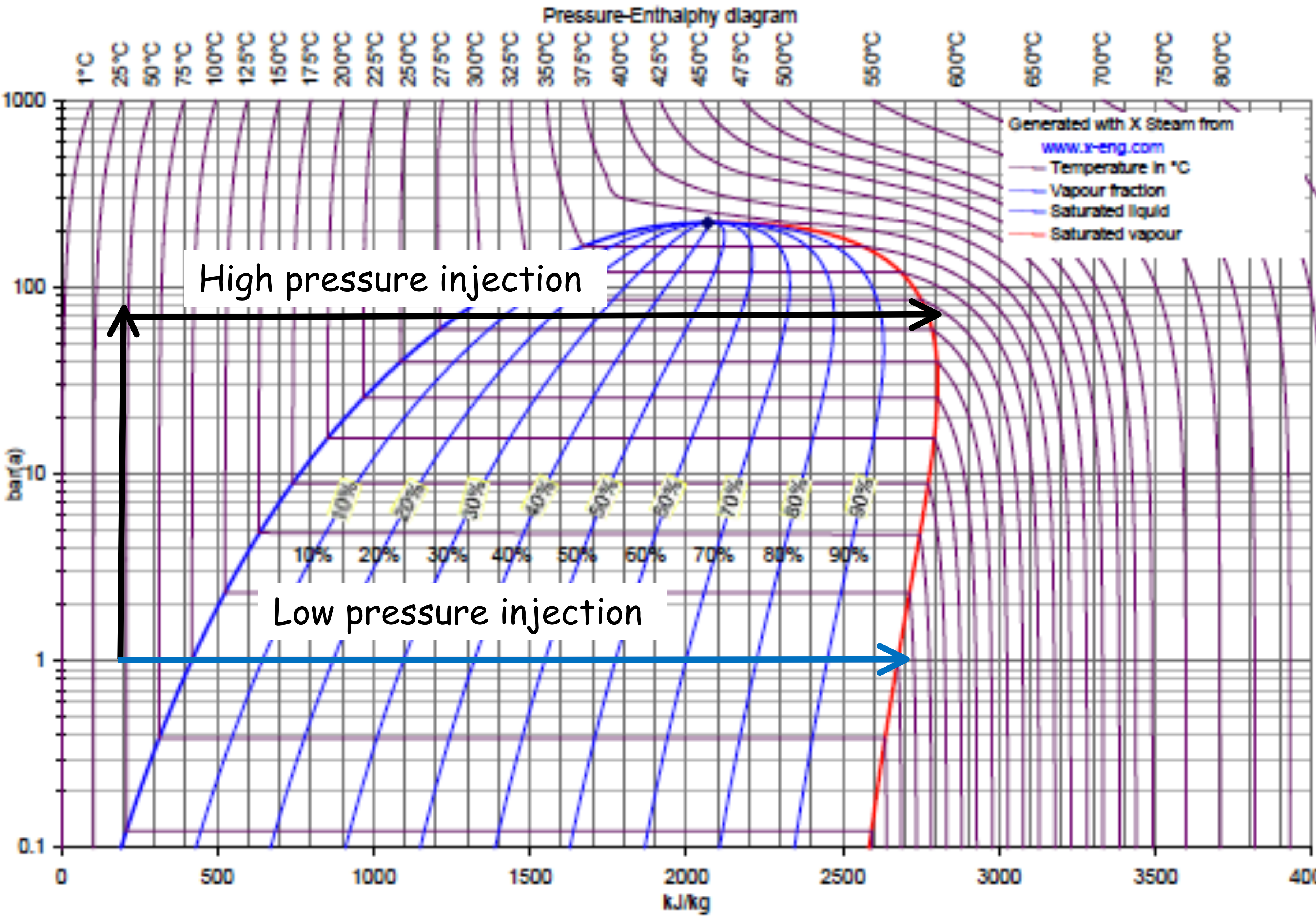


Energy balance

$$(H_{out} - H_{in})\dot{M} = \dot{Q}$$

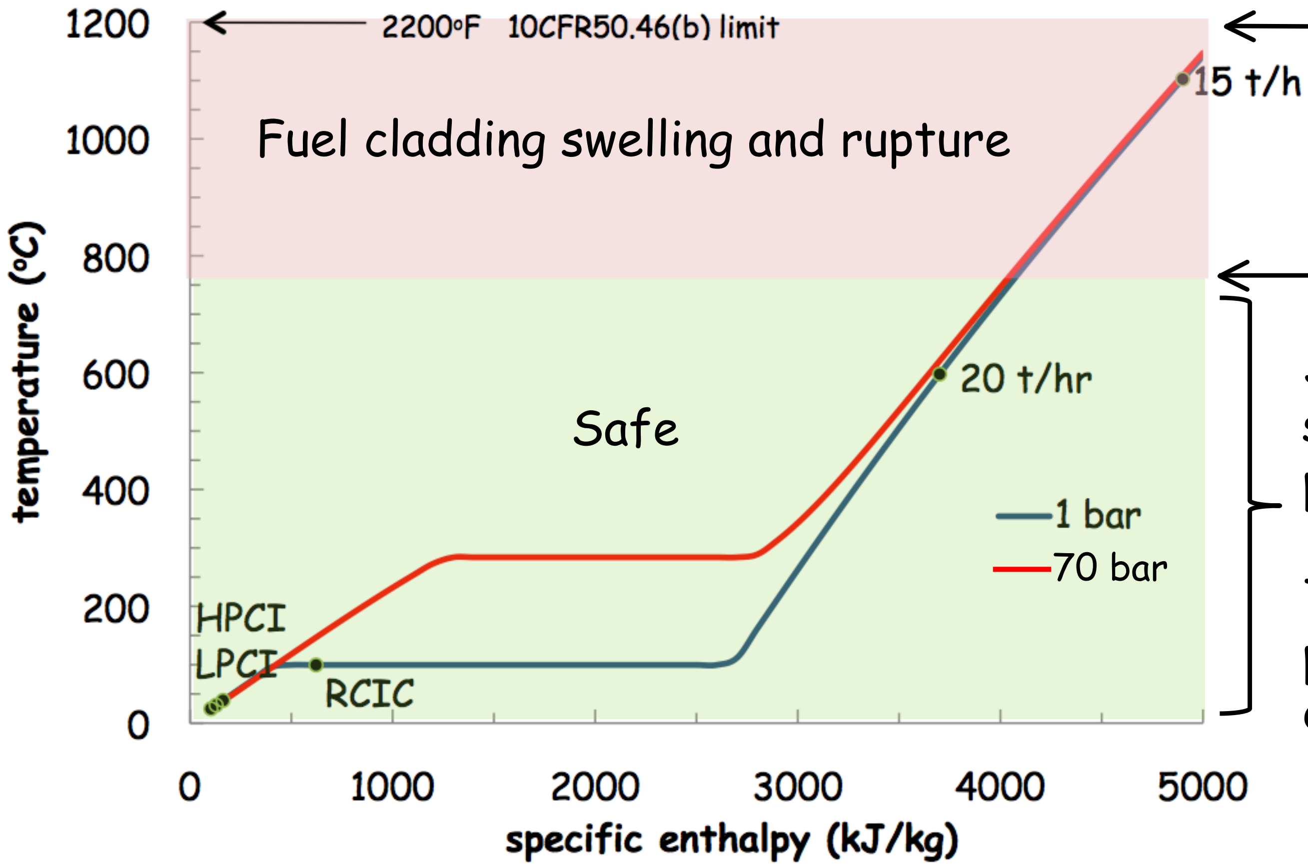
$$\dot{Q} = 20 \text{ MW}$$

Capability	$\dot{M}$ (t/h)	H (kJ/kg)	T °C
Portable pumps	15	4800	1103
RCIC	138	522	100
HPCI	1134	63	39
LPCI	2478	29	31
Main feedwater	21600	3	25



Pressure-Enthalphy diagram
1°C
25°C
50°C
75°C
100°C
125°C
150°C
175°C
200°C
225°C
250°C
275°C
300°C
325°C
350°C
375°C
400°C
425°C
450°C
475°C
500°C
550°C
600°C
650°C
700°C
750°C
800°C
Generated with X Steam from
www.x-eng.com
Temperature in °C
Vapour fraction
Saturated liquid
Saturated vapour
High pressure injection
Low pressure injection
10%
20%
30%
40%
50%
60%
70%
80%
90%
1000
100
10
1
0.1
bar(a)
0
500
1000
1500
2000
2500
3000
3500
4000
kJ/kg

崩壊熱除去の見積もり



Onset of H2 generation

Onset of fuel swelling

Stable situation, steady heat removal possible.

Temperatures and pressures will slowly decrease.

Caution: Extremely simplistic “back of the envelope” estimate!

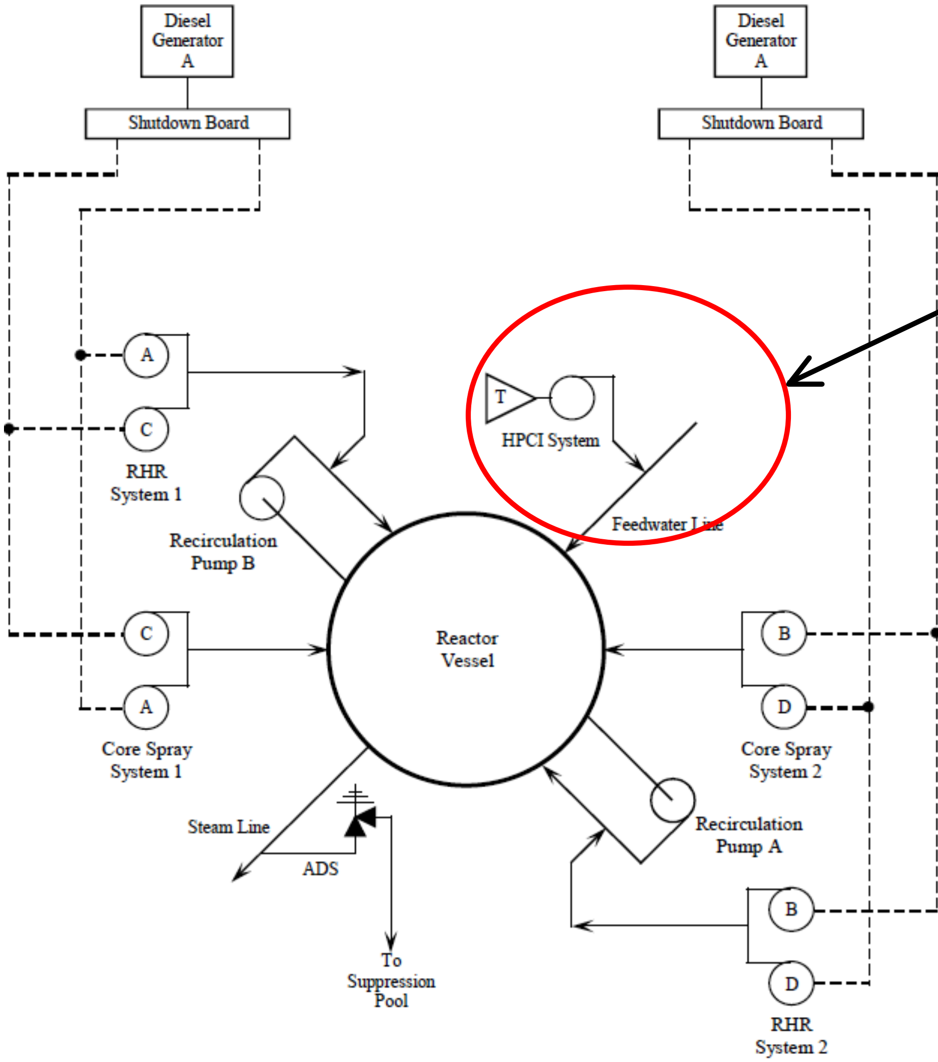
事故管理:通常時

- 核反応の制御ー制御棒のコントロール／中性子吸収
- 原子炉圧力容器内の水量を保つ
  - 核燃料を冷却水中に保つため
  - ジルコニウム被膜からの水素発生を防ぐ
- 原子力圧力容器の圧力を限界以下に保つ
- 格納容器内の圧力を限界以下に保つ
- サプレッションプールの水を沸点以下に保つ
- サプレッションプール／排気筒を通じてベントする

事故後の熱除去および熱制御用の冷却システム

- ホウ酸水注入系- ホウ素による中性子吸収
- 非常用炉心冷却装置
  - 高圧炉心注水系
  - 原子炉隔離時冷却系
  - 自動減圧系
  - 低圧注水系
  - コアスプレー

非常用炉心冷却装置(ECCS)に必要な遠隔又は非常用ディーゼルエンジン



RCICは蒸気駆動で、バルブ操作のみが必要

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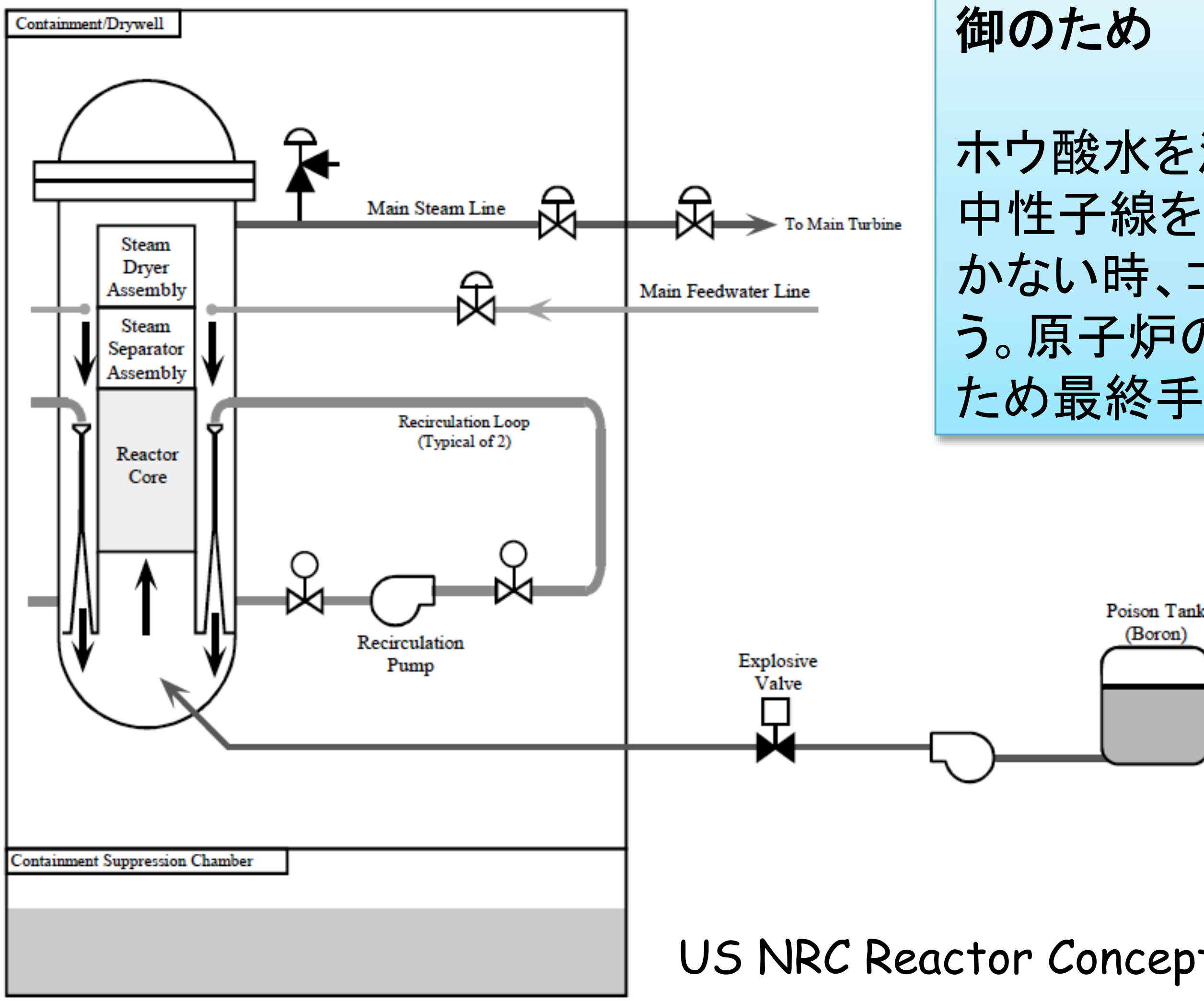
ホウ酸水注入系 (SLC)



熱除去のためではなく、核反応制御のため

ホウ酸水を注入することでコアの中性子線を吸収する。制御棒が働かない時、コアが破壊された時使う。原子炉の再使用ができなくなるため最終手段とされている。

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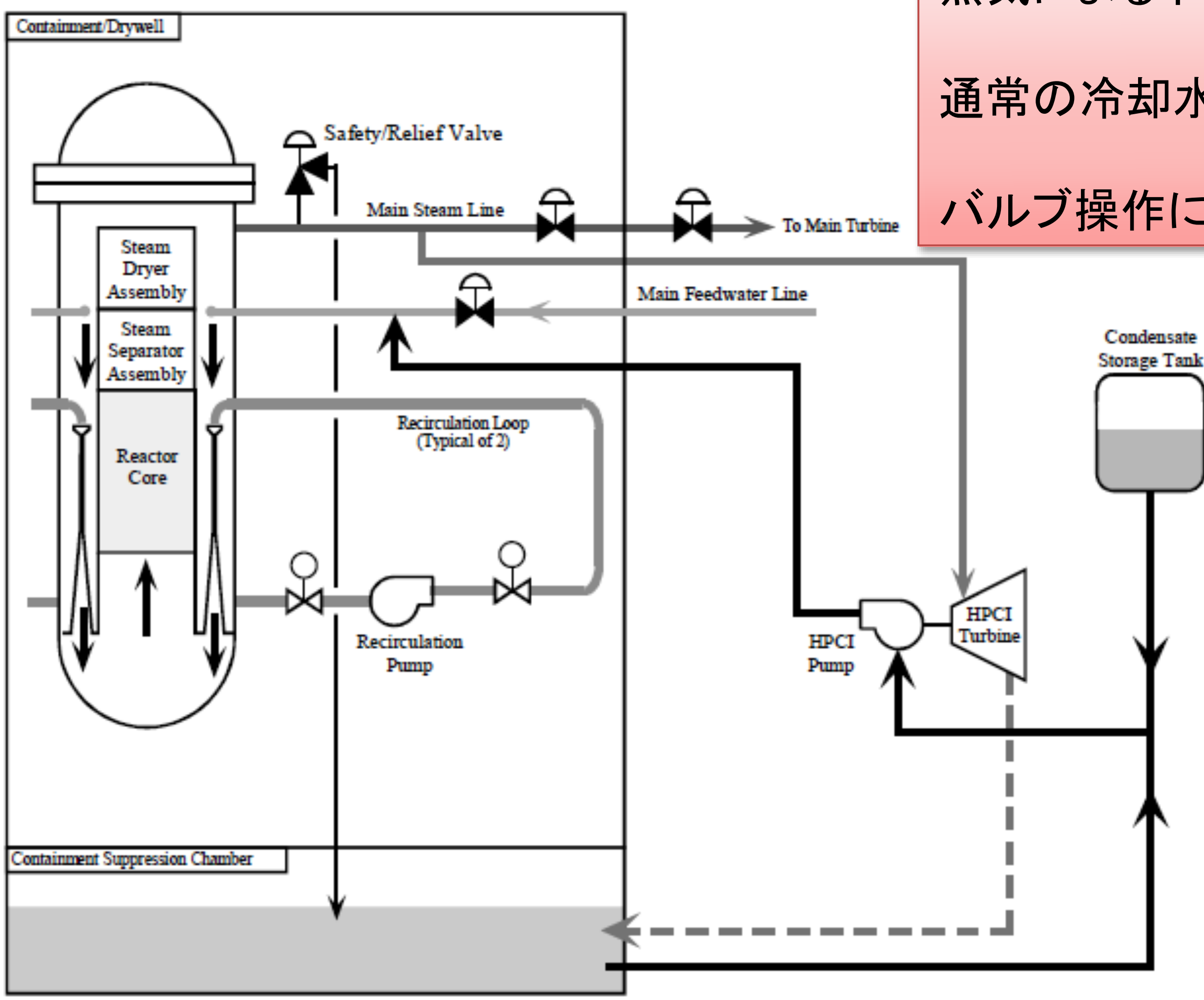
高圧ECCS（非常用炉心冷却装置）ー原子炉隔離時冷却（RCIC）

蒸気によるポンプの起動

通常の冷却水が供給できない時に用いる

バルブ操作に電力が必要



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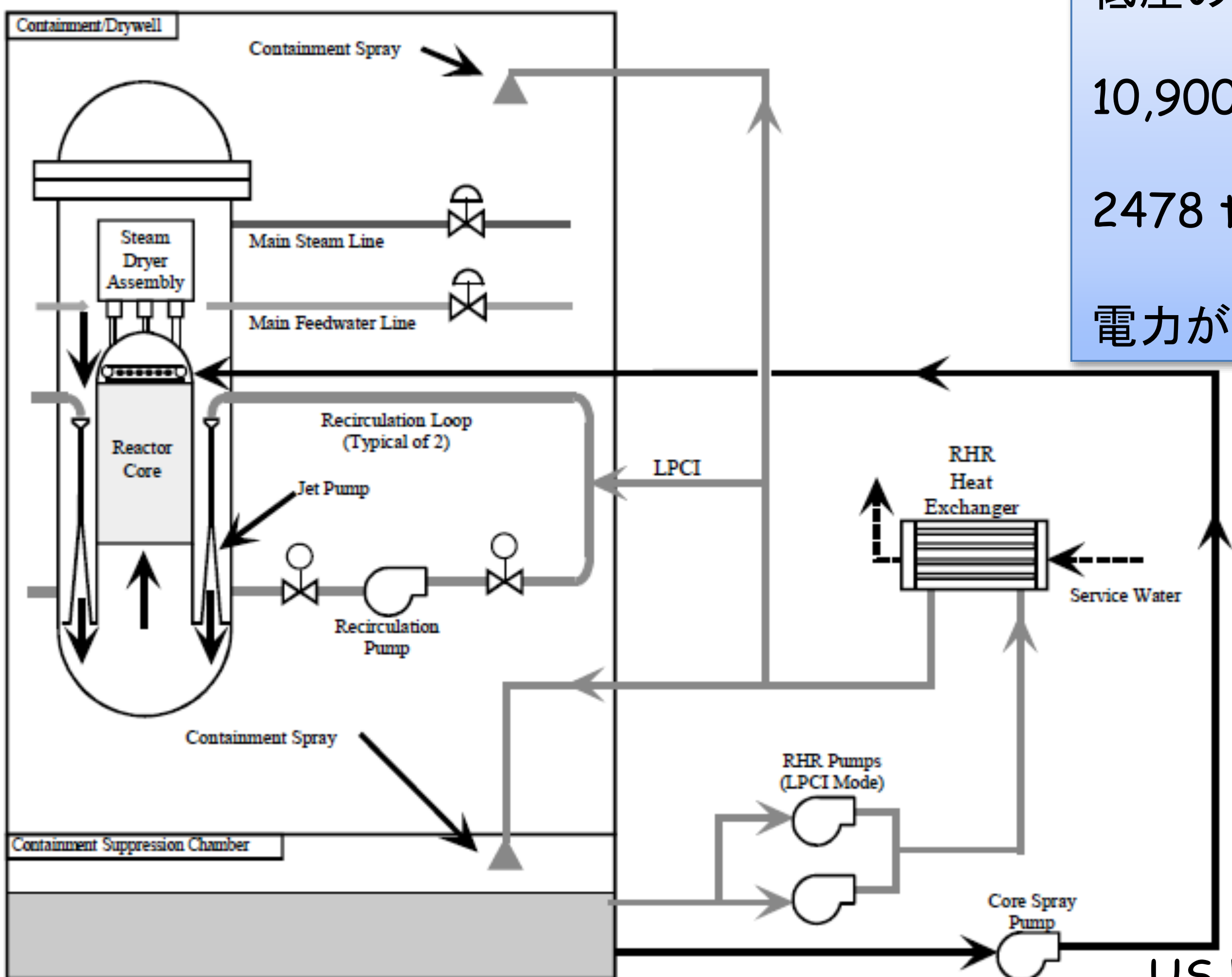
低圧 ECCS - 低圧注水(LPCI)



低圧のシステム

10,900 gpm @ 20 psig

2478 tonne/h 136 kPa

電力が必要

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幾重にもおよぶ事故防止システムリスト

何重もの

核反応制御系

注水およびに熱除去系

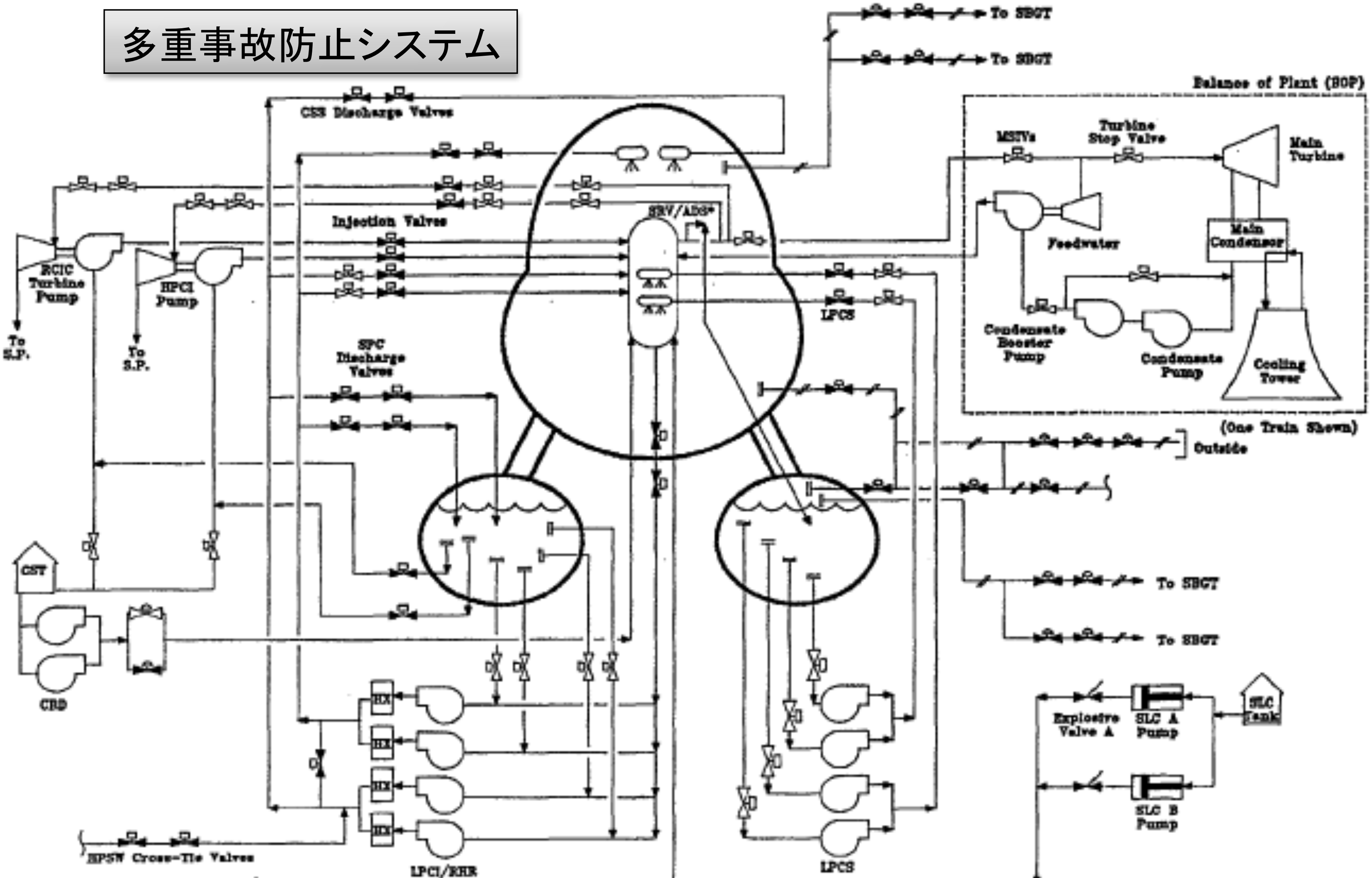
核分裂生成物が放出されないための防護

Table 4.1 Summary of design features: Peach Bottom Unit 2.

1. Coolant Injection Systems	a.	High-pressure coolant injection system provides coolant to the reactor vessel during accidents in which system pressure remains high, with 1 train and 1 turbine-driven pump.
	b.	Reactor core isolation cooling system provides coolant to the reactor vessel during accidents in which system pressure remains high, with 1 train and 1 turbine-driven pump.
	c.	Low-pressure core spray system provides coolant to the reactor vessel during accidents in which vessel pressure is low, with 2 trains and 4 motor-driven pumps.
	d.	Low-pressure coolant injection system provides coolant to the reactor vessel during accidents in which vessel pressure is low, with 2 trains and 4 pumps.
	e.	High-pressure service water crosstie system provides coolant makeup source to the reactor vessel during accidents in which normal sources of emergency injection have failed (low RPV pressure), with 1 train and 4 pumps for crosstie.
	f.	Control rod drive system provides backup source of high-pressure injection, with 2 pumps/210 gpm (total)/1,100 psia.
	g.	Automatic depressurization system for depressurizing the reactor vessel to a pressure at which the low-pressure injection systems can inject coolant to the reactor vessel: 5 ADS relief valves/capacity 820,000 lb/hr. In addition, there are 6 non-ADS relief valves.
2. Key Support Systems	a.	dc power with up to approximately 10–12-hour station batteries.
	b.	Emergency ac power from 4 diesel generators shared between 2 units.
	c.	Emergency service water provides cooling water to safety systems and components shared by 2 units.
3. Heat Removal Systems	a.	Residual heat removal/suppression pool cooling system to remove heat from the suppression pool during accidents, with 2 trains and 4 pumps.
	b.	Residual heat removal/shutdown cooling system to remove decay heat during accidents in which reactor vessel integrity is maintained and reactor at low pressure, with 2 trains and 4 pumps.
	c.	Residual heat removal/containment spray system to suppress pressure and remove decay heat in the containment during accidents, with 2 trains and 4 pumps.
4. Reactivity Control Systems	a.	Control rods.
	b.	Standby liquid control system, with 2 parallel positive displacement pumps rated at 43 gpm per pump, but each with 86 gpm equivalent because of the use of enriched boron.
5. Containment Structure	a.	BWR Mark I.
	b.	0.32 million cubic feet.
	c.	56 psig design pressure.
6. Containment Systems	a.	Containment venting—drywell and wetwell vents used when suppression pool cooling and containment sprays have failed to reduce primary containment pressure.

NUREG 1150

多重事故防止システム

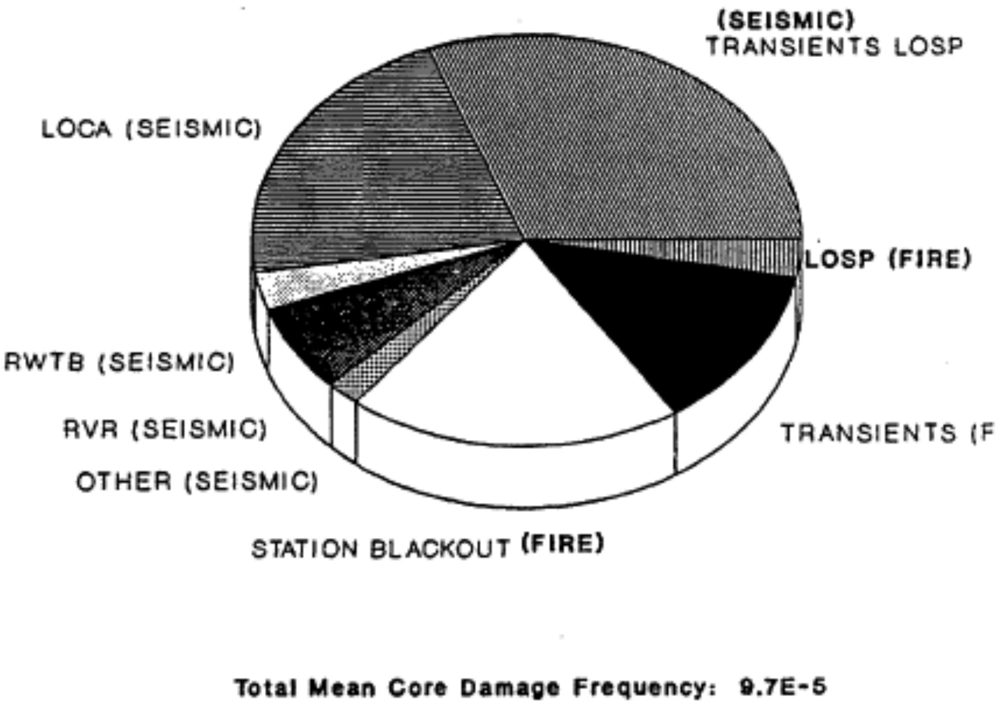


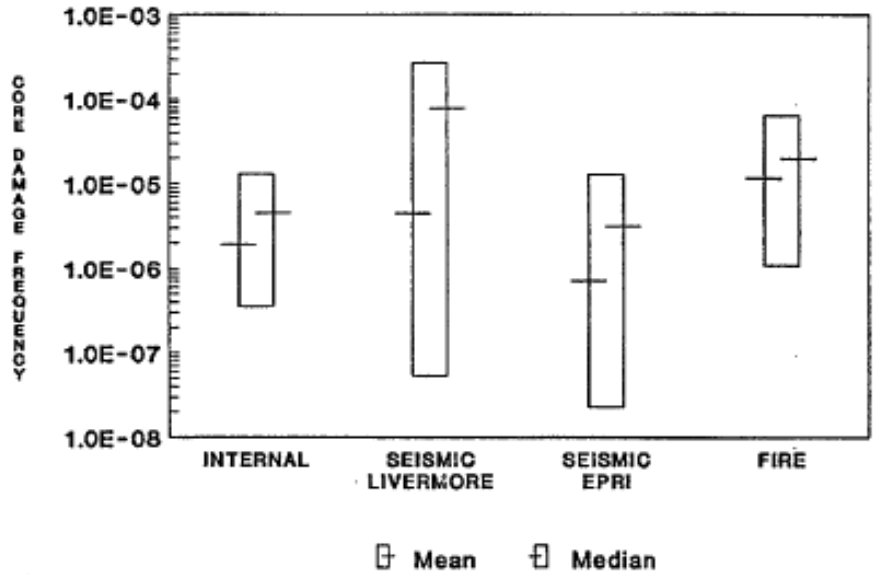
*Typical arrangement (5 ADS SRVs and 6 non-ADS SRVs)

NUREG-1150

炉心にダメージが起こる可能性

1/10,000 炉心-年





NUREG-1150 Peach Bottom results –frequency is per reactor-year of operation

リスク要因

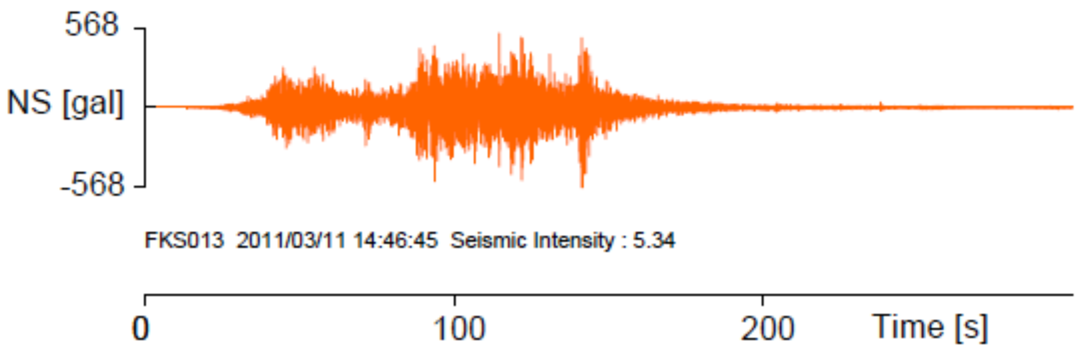
The risk from the internal events are driven by long-term station blackout (SBO) and anticipated transients without scram (ATWS). The dominance of these two plant damage states can be attributed to both general BWR characteristics and
plant-specific design. BWRs in general have more redundant systems that can inject into the reactor vessel than PWRs and can readily go to low pressure
and use their low-pressure injection systems. This means that the dominant plant damage states will be driven by events that fail a multitude of systems (i.e., reduce the redundancy through some common-mode or support system failure) or
events that only require a small number of systems to fail in order to reach core damage. The station blackout plant damage state satisfies the first of these requirements in that all systems ultimately depend upon ac power, and a loss of offsite power is a relatively high probability event. The total probability of losing ac power long enough to induce core damage is relatively high, although still
low for a plant with Peach Bottom's design. The ATWS scenario is driven by the small number of systems that are needed to fail and the high stress upon the operators in these sequences.   NUREG 1150 4.6.2

危機下にある4つの原子炉
Four Reactors in Crisis

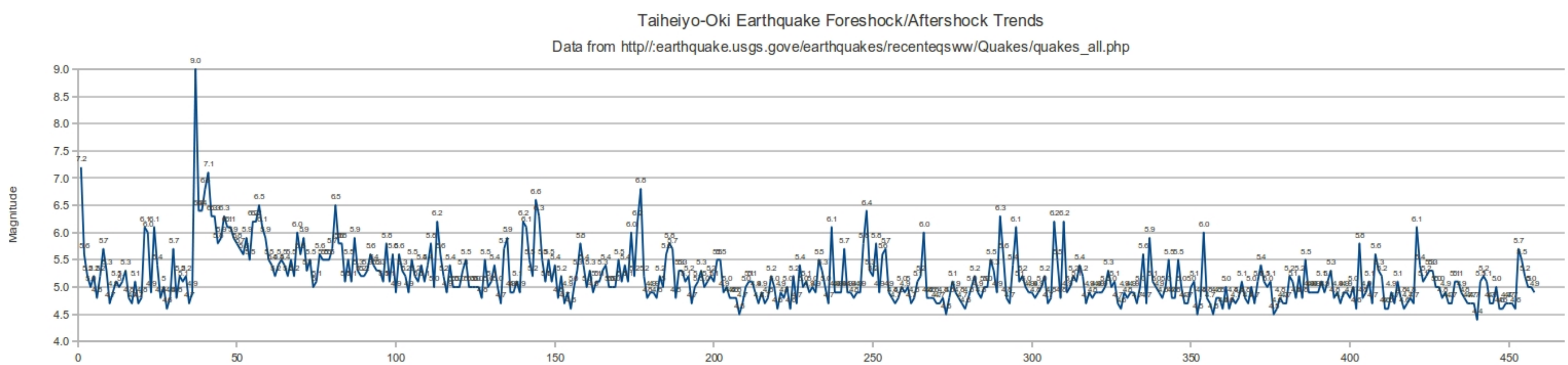
3月11日以前の福島第一原子力発電所1~4号機

Digital Globe

巨大地震 500 gal > 設計用最強地震動 250 gal

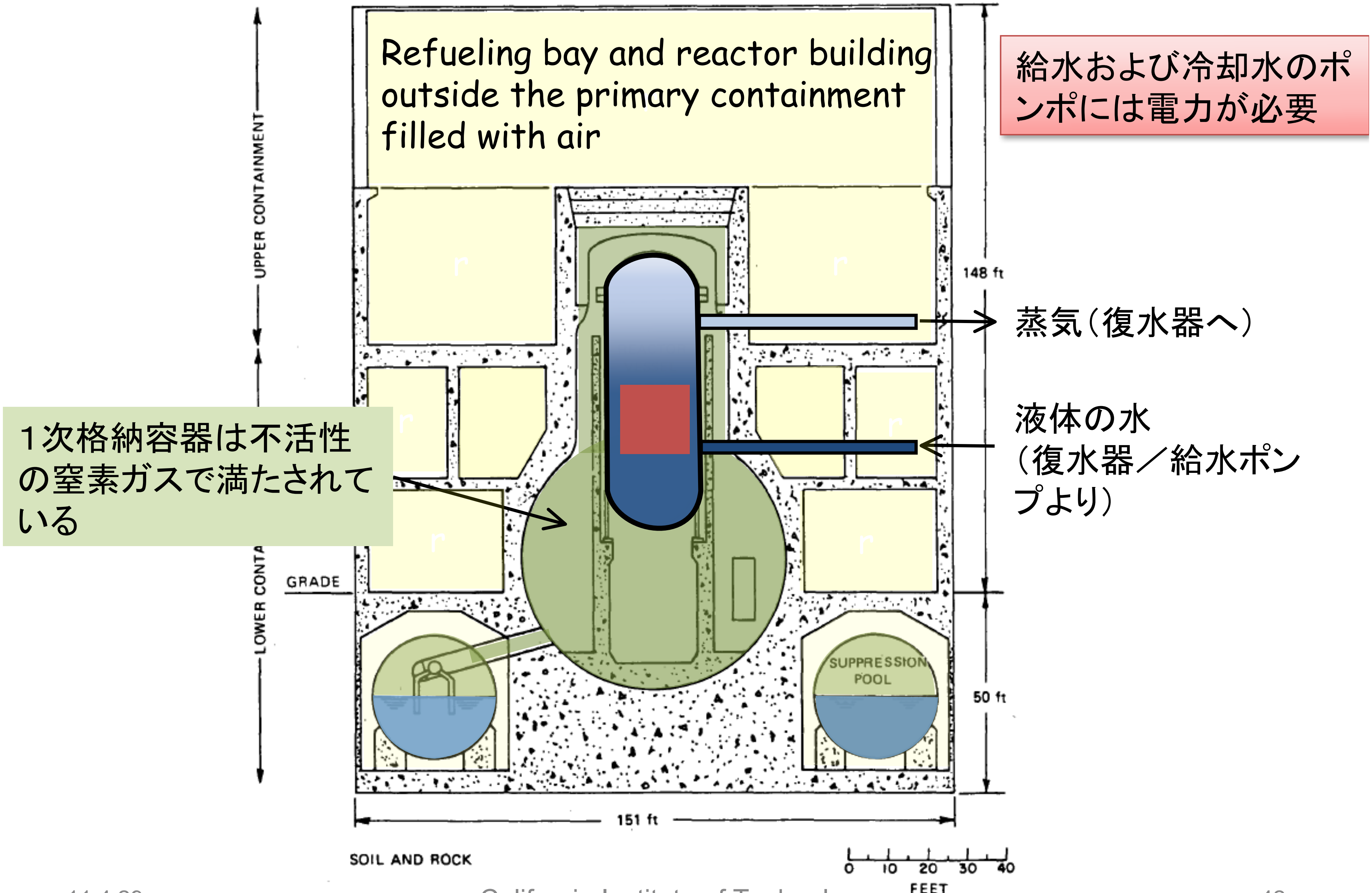


Electrical grid failed, Loss of Offsite Power (LOOP) and shaking initiated reactor shutdown



NIED and USGS

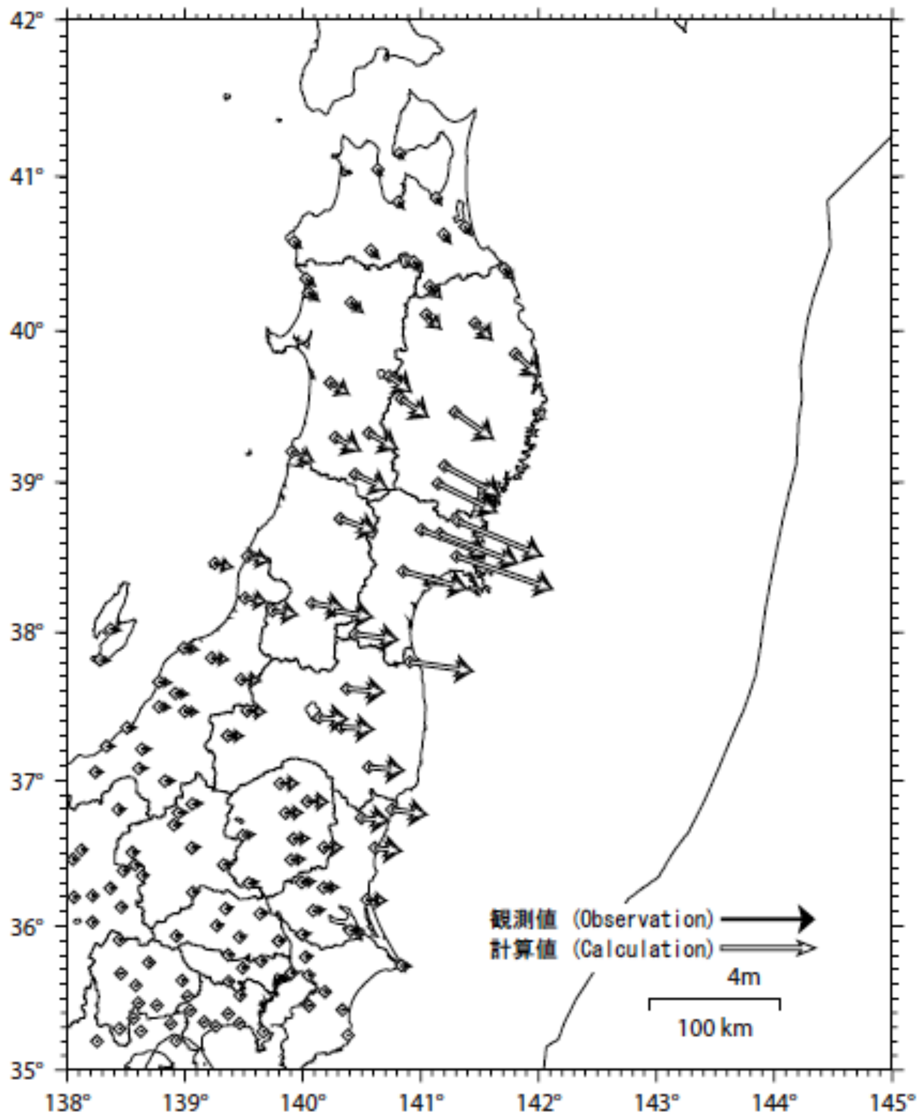
復水器による通常の冷却過程

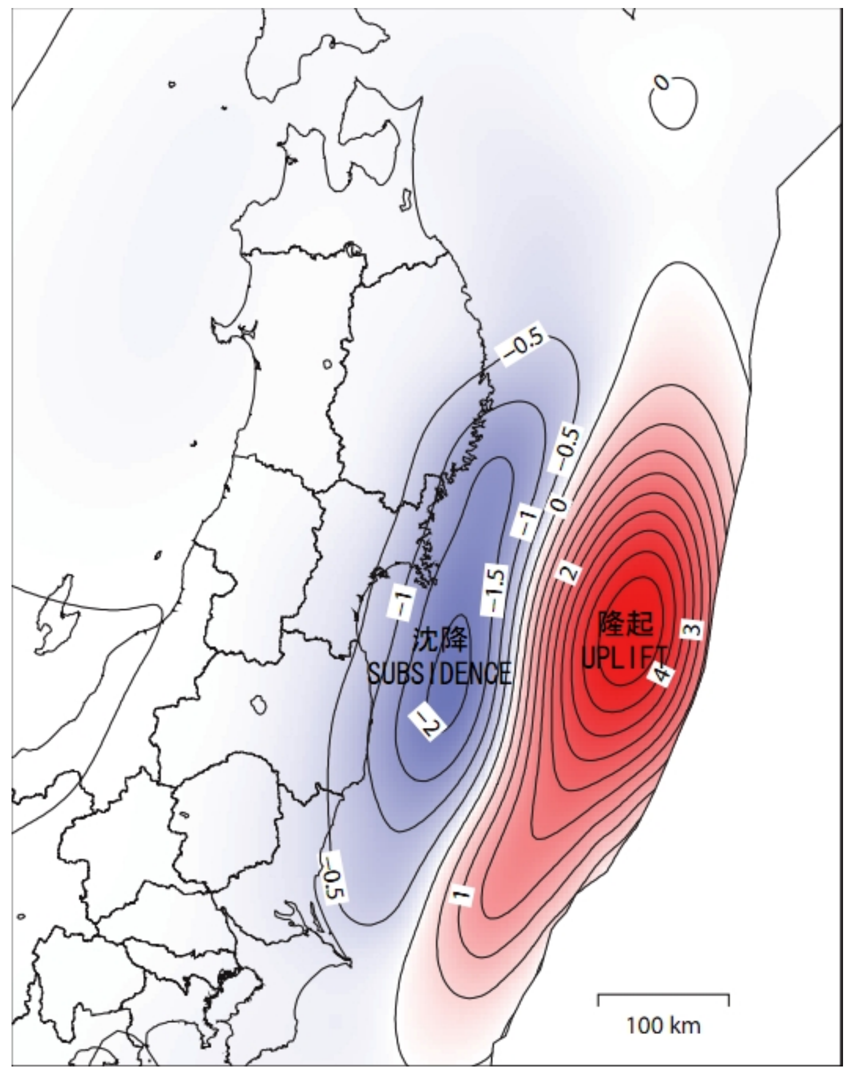


巨大津波 10-15 m > 設計時想定 6 m

沿岸域における地盤沈下

http://www.gsi.go.jp/cais/topic110315-index-e.html





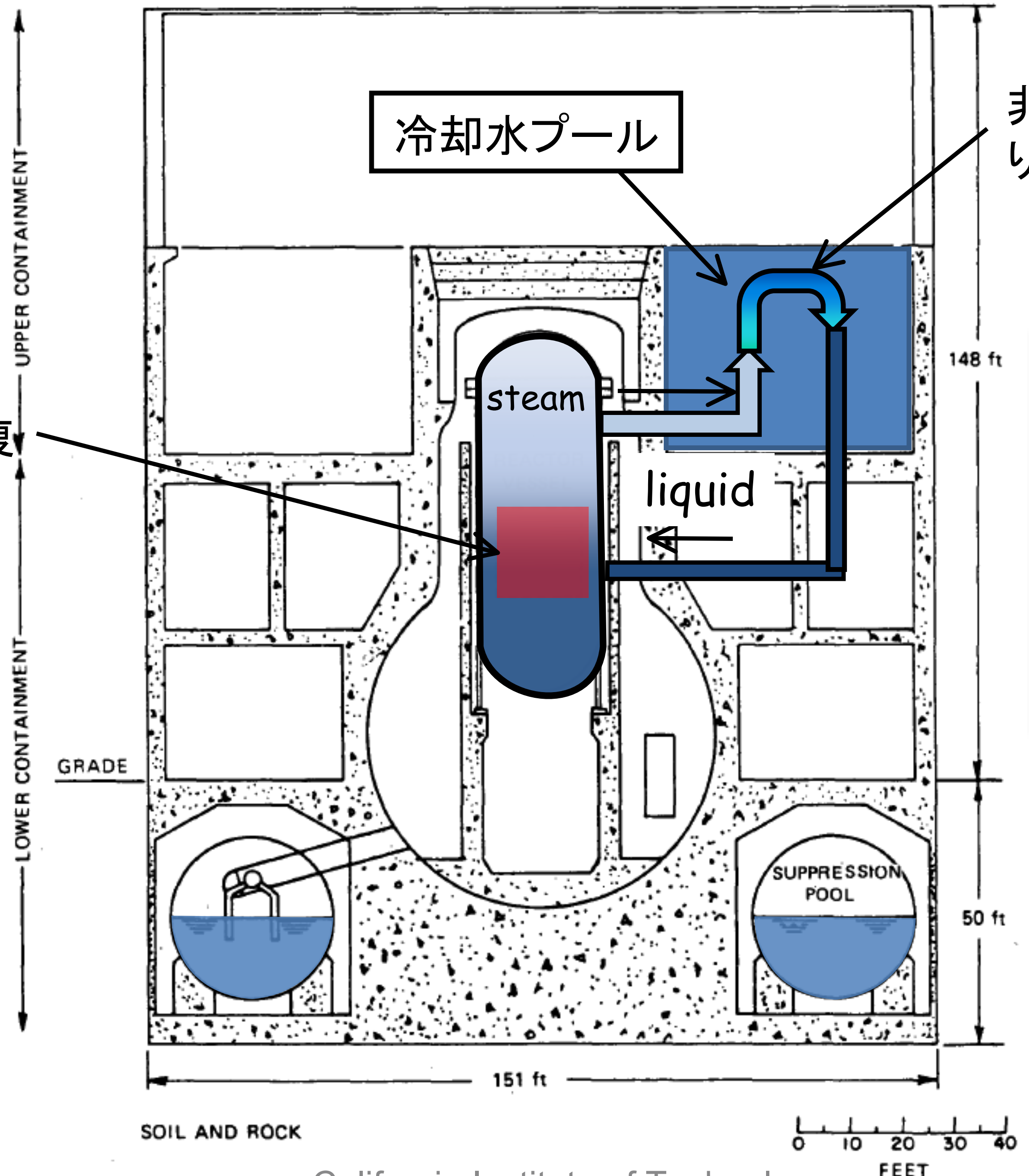
非常用電源の故障

http://photoblog.msnbc.msn.com/

Friday, March 11, 2011				
	14:46:00	11.62	0.00	Tohoku-Pacific megathrust earthquake magnitude 9.0, shaking at Fukushima 1 was about 500 cm/S^2
	14:48:00	11.62	0.00	Reactors and turbines shut down. Control blades inserted into units 1, 2, and 3 and main steam isolation valve closed. Residual heat removal started. Loss of -site power, diesel engines started to provide electrical power.
	15:41:00	11.65	0.88	Tsunami reaches Fukushima. Wave initially estimated at 10 m and revised to be up to 23 m overtops 6.5 m barrier. Diesel generators stop, power switched to battery backup.
	15:42:00	11.65	0.90	Article 10 emergency reported by Tepco for units 1, 2, and 3.
	16:36:00	11.69	1.80	Batteries fail in Unit 1
	16:45:00	11.70	1.95	Article 15 nuclear emergency declared for units 1 and 2 because ECCS function could not be confirmed.
	17:07:00	11.71	2.32	Article 15 Emergency cleared when water level was determined then reinstated for Unit 1.
	17:07:00	11.71	2.32	Unit 1 cooled by isolation condenser. Units 2 and 3 cooled by Reactor Core Isolation Cooling System.
	18:08:00	11.76	3.33	Unit 1 of Fukushima 2 declared to be in Article 10 emergency.
	18:33:00	11.77	3.75	Units 2, 3, and 4 of Fukushima 2 declared to be in Article 10 emergency.
	19:03:00	11.79	4.25	Government declared state of nuclear emergency.
	20:50:00	11.87	6.03	1864 people within 2 km of plant evacuated.

１号機で
バッテリー
切れにより
電源喪失
→ (16:36:00)

1号機：非常用復水器 (Isolation Condenser)



炉心における崩壊熱が蒸気を発生させ、非常用復水器への循環をさせる

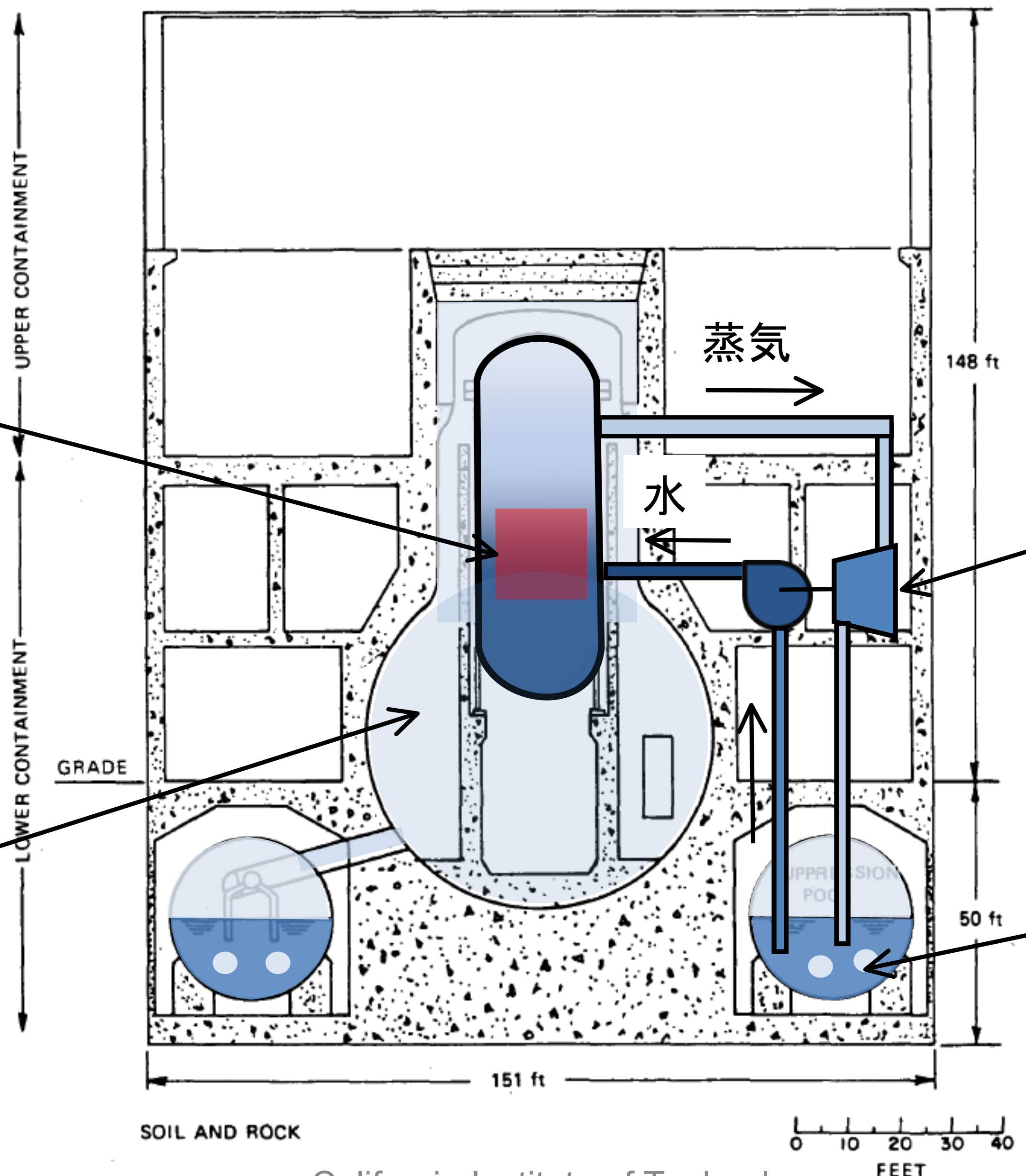
非常用復水器は熱を周りのプールにうつす

プールから余剰の熱を奪うシステムが働いていないため、この冷却は限られた時間しか働かない。やがて水は沸騰してなくなる。

2・3号機：原子炉隔離時冷却系(RCIC)

過剰の熱を除くシステムが働いていないため、冷却は一定期間しか起こらない

炉心における崩壊熱がポンプを動かす蒸気を生じる



RCIC
蒸気タービンがポンプを回す

サプレッションプールが温度上昇するにつれ、一次格納容器は蒸気で満たされる

サプレッションプールで蒸気が水に戻る

原子力安全制度の見直し

<Special Act for Nuclear Emergency>

Outcome of 1999 JCO accident
At Tokai-mura, Japan

(1) To ensure swift initial activation (Article 10)

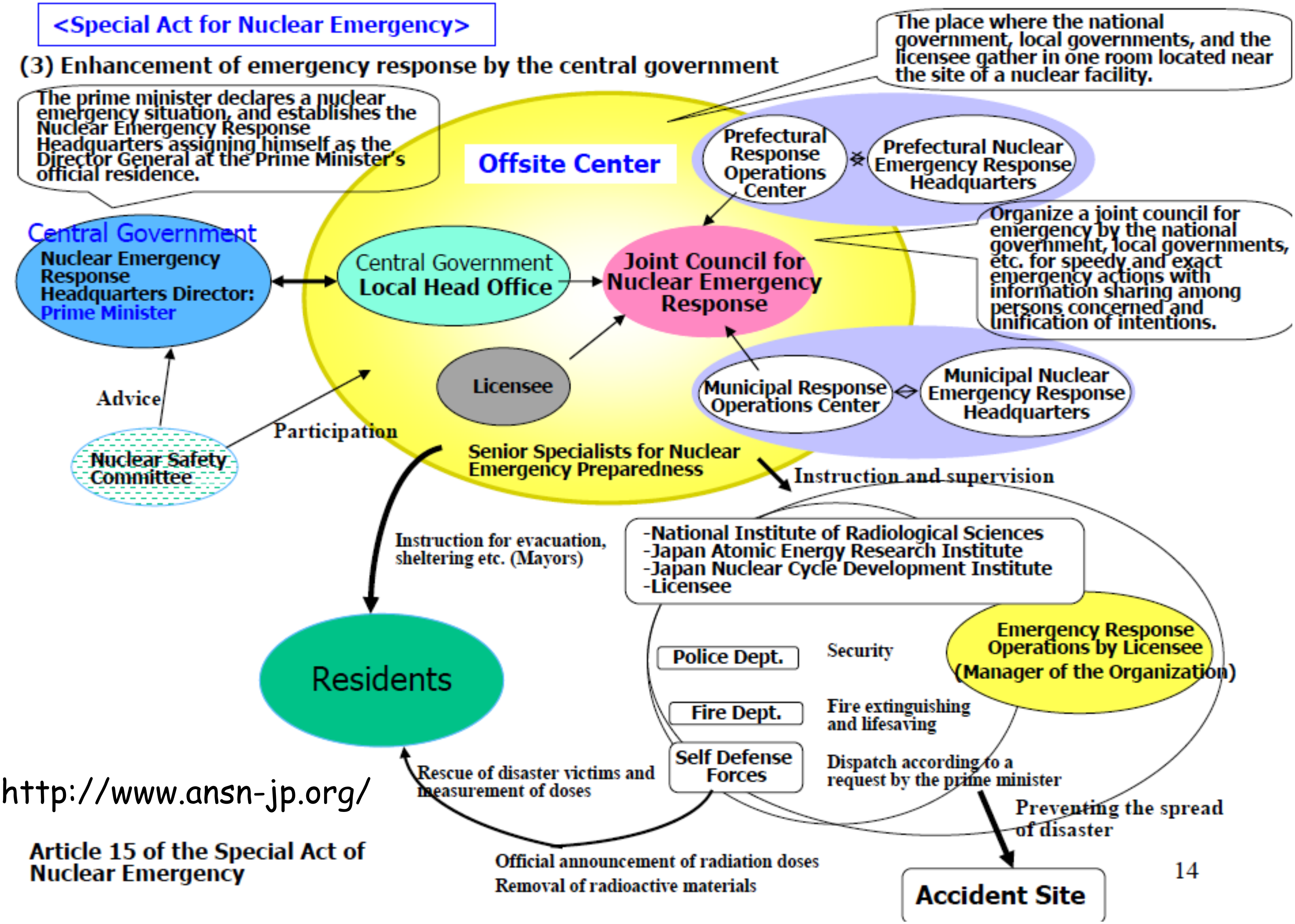
A) Clarification of the notification criteria → **Notification by the licensee**

B) Clarification of the decision criteria for nuclear emergency → **Establishment of the "Nuclear Emergency Response Headquarters " and the "Local Nuclear Emergency Response Headquarters "**

Notification criteria	Decision criteria for nuclear emergency
● When radiation doses of 5micro-Sv/h or more for ten minutes or more are detected with radiation measuring equipment installed near the site boundary. ● When radioactive materials equivalent to 5micro-Sv/h for ten minutes or more are detected at the site boundary with considering diffusion etc. from the normal release point such as a ventilation stack. ● When radiation doses of 50micro-Sv/h for continuous ten minutes or more or radioactive materials equivalent to 5micro-Sv/h are detected in the vicinity of the controlled area. ● When radiation doses of 100micro-Sv/h or more are detected at a point one meter away from a shipping cask ● When the possibility of criticality at a facility other than the nuclear reactor core. ● When an incident occurred according to the characteristic of each plant that may result in a nuclear emergency such as a situation incapable of reactor shutdown by control rods.	● Detection of radiation doses of 500micro-Sv/h or more with radiation measuring equipment installed by the licensee near the site boundary or installed by the prefecture concerned. ● Detection of one-hundred times of numeric values of the notification event at a normal release point such as a ventilation stack, in the vicinity of a controlled area, or at a point one meter away from a shipping cask. ● A criticality state at a facility other than in the nuclear reactor core. ● An incident according to the characteristic of each plant that indicates the occurrence of a nuclear emergency situation such as a situation incapable of shutting down the liquid neutron absorber(boric acid solution) in addition to control rod insertion. http://www.ansn-jp.org/ 12

<Special Act for Nuclear Emergency>

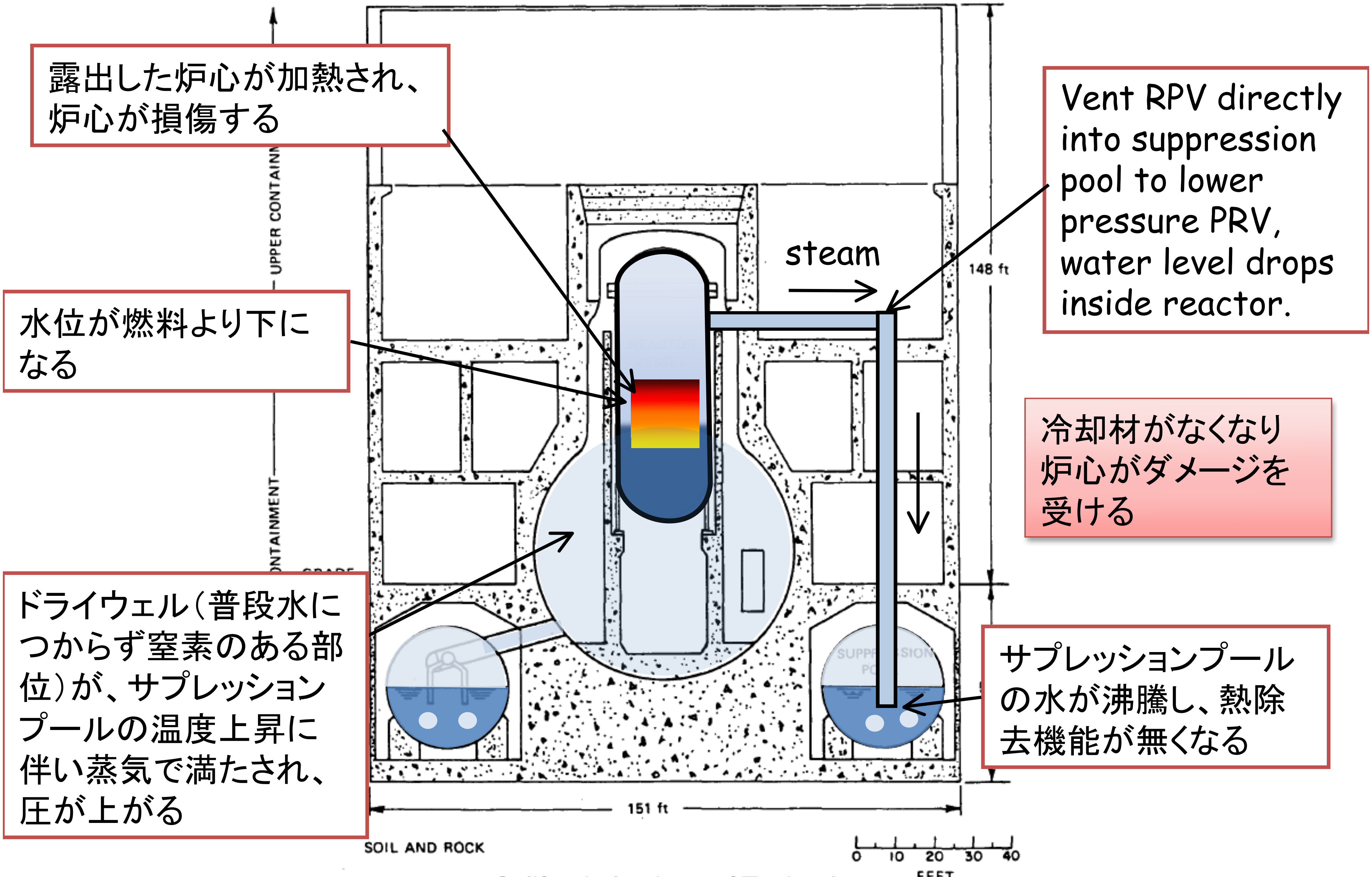
(3) Enhancement of emergency response by the central government



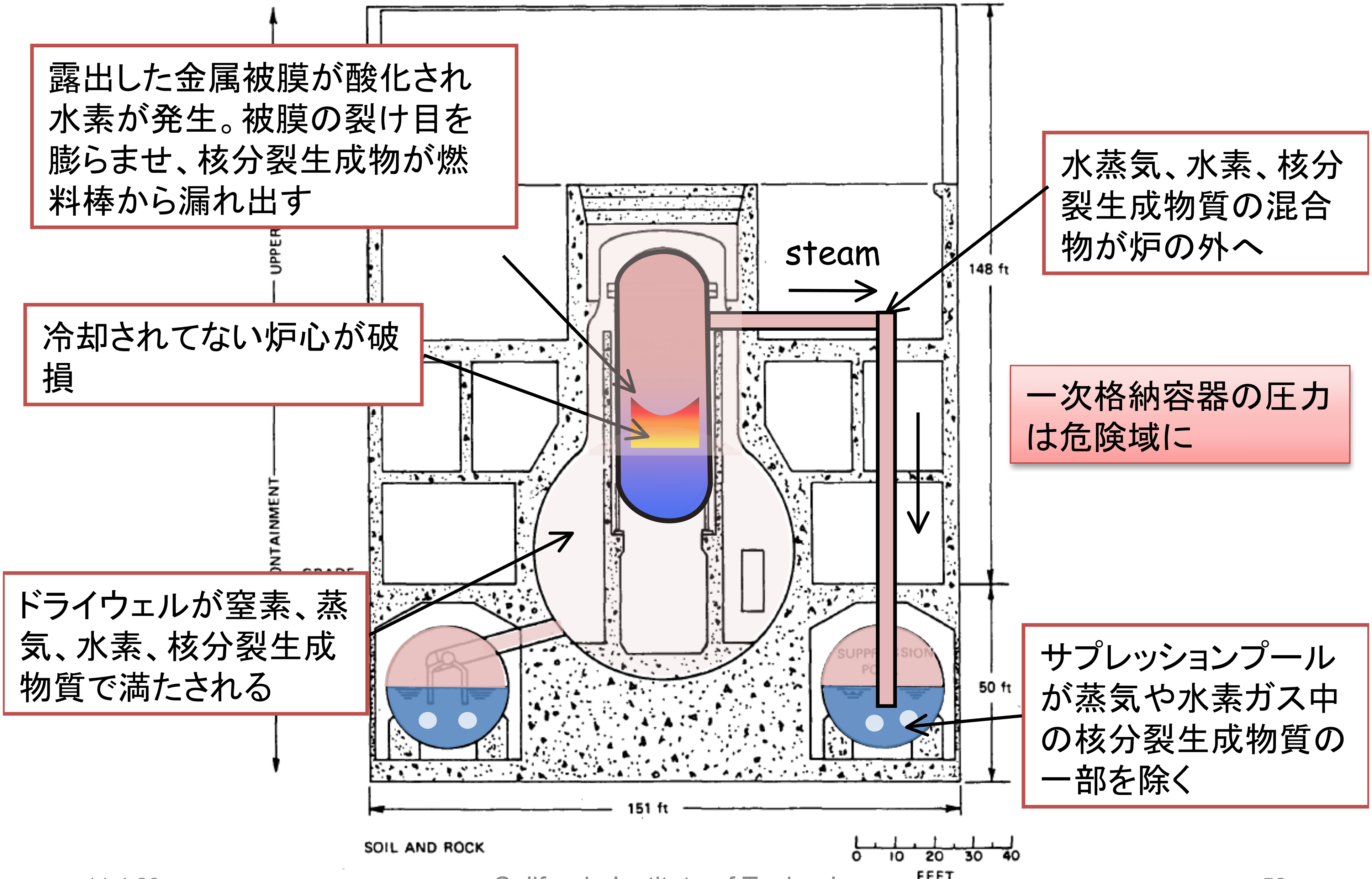
http://www.ansn-jp.org/

Article 15 of the Special Act of Nuclear Emergency

プール温度の上昇とポンプの停止により緊急冷却機能が喪失



破損した炉心が核分裂生成物質を放出し、水素を発生させた



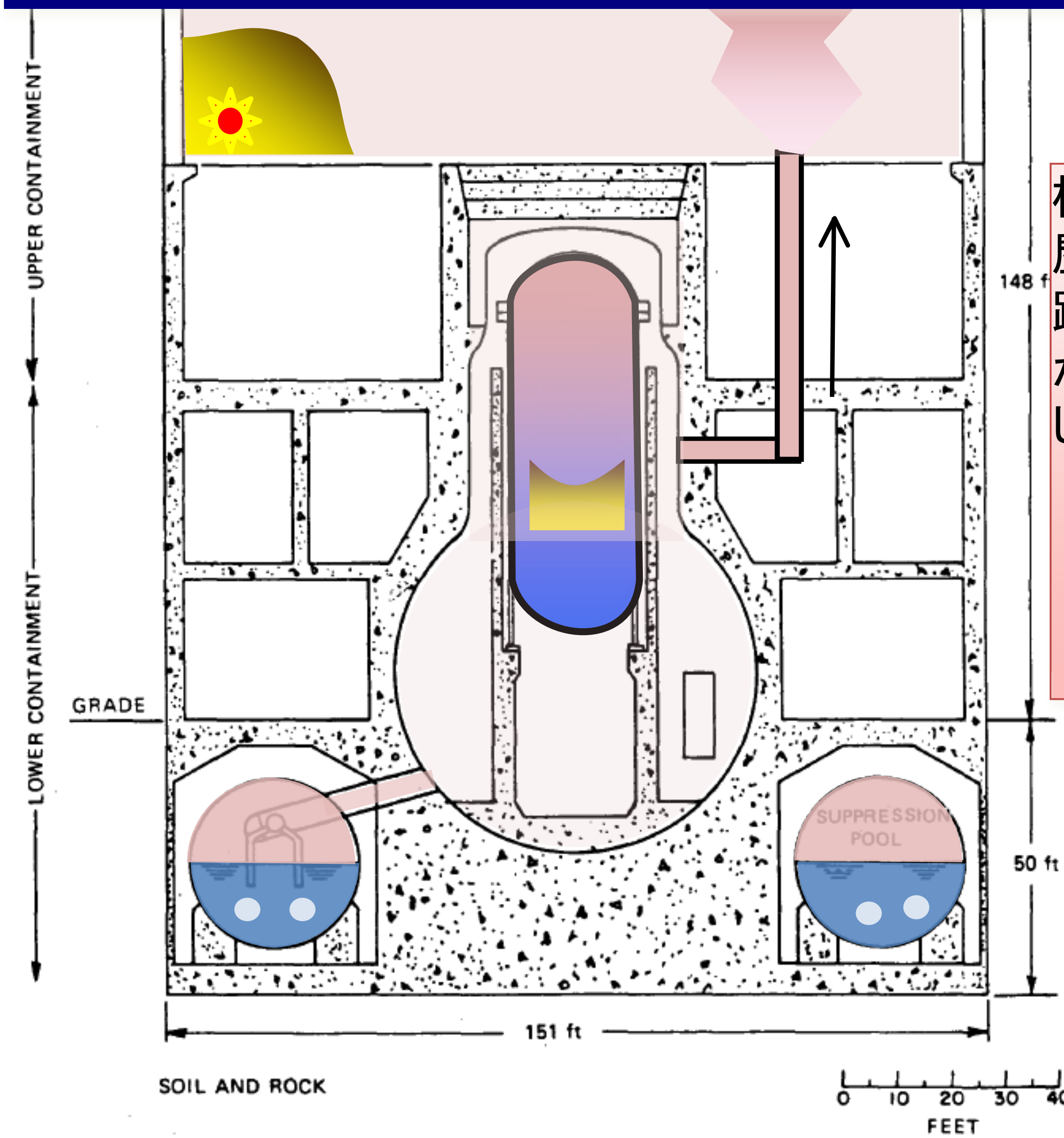
2011年3月12日

	1:20:00	12.06	10.53	Unusual pressure rise in PCV Unit 1 - Article 15 notification.
	2:00:00	12.08	11.20	Unit 1 primary containment at 600 kPa
	5:30:00	12.23	14.70	Unit 1 primary containment at 820 kPa
	5:40:00	12.24	14.87	Evacuation zone extended to 10 km
	6:50:00	12.28	16.03	Government give order to vent.
	9:00:00	12.38	18.20	Planning to vent
	10:17:00	12.43	19.48	Unit 1 primary containment venting to atmosphere.
		12.44	19.76	0.38 mSv/hr spike at front gate MP
	11:20:00	12.47	20.53	90 cm of fuel rods exposed in Unit 1. Final assessment (March 16) is 70 % damage to fuel.
		12.51	21.44	0.05mSv/hr spike at front gate MP
	13:30:00	12.56	22.70	Water level dropping in unit 1
	13:30:00	12.56	22.70	Ce-137 and I--131 detected near unit 1
	14:40:00	12.61	23.87	Steam release from primary of Unit 1
	15:29:00	12.65	24.68	Radiation dose at site boundary exceeds limit value at MP4 and Article 15 emergency declared at 16:17.
	15:36:00	12.65	24.80	Large quake followed by explosive sound and large white cloud from unit 1. Later determined to be explosion inside refueling bay, all panels blown off reactor building above the refueling floor level. Presumed to be H2 released into building by primary containment venting. 4 workers injured.
	25:00	12.77	27.62	Prime minister orders evacuation to 20 km
		12.81	28.64	0.025mSv/hr spike at front gate MP
	19:55:00	12.83	29.12	Prime minister order sea water injection into unit 1
	20:00:00	12.83	29.20	RCICS shut down in Unit 2. RCICS still running in Unit 3.
	20:20:00	12.85	29.53	Seawater injection into core of Unit 1 started, followed by borated water injection. Using fire lines to inject. 2 m3/hr
	20:41:00	12.86	29.88	Starting to vent Unit 3.
	22:15:00	12.93	31.45	Injection in unit 1 stopped due to quake.
	23:00:00	12.96	32.20	No ECCS in Unit 2, low water level, getting ready to vent.

一号機水素爆発
3月12日時刻15:36
地震発生から24.8時間後

Vent Primary Containment to Reduce Pressure

格納容器内の圧力を低下させるために、弁を解放し気体を外部に放出させる操作（ベント）が実施された



格納容器内の気体を建屋内へ放出。詳しい経路は不明だが水素ガスが建屋内の空気と反応し爆発発生。

1号機　水素爆発　（画像：ロイター）

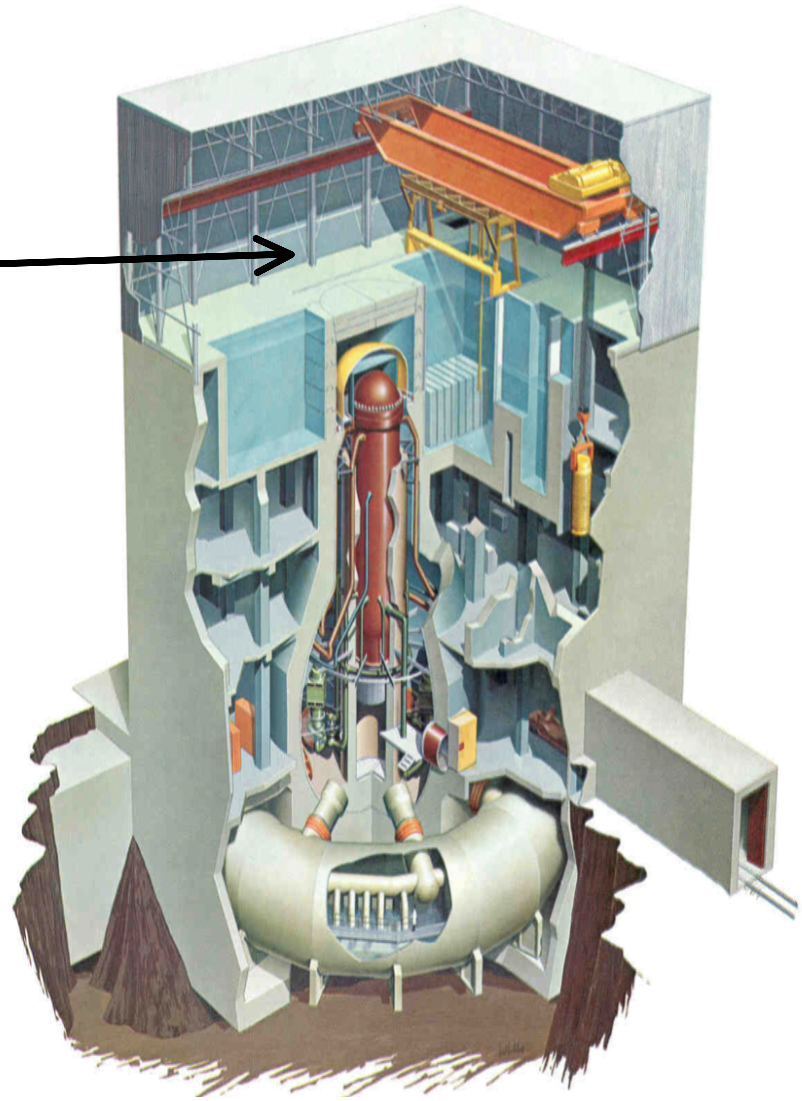
Unit 1 Explosion

Reuters

爆発の様子のビデオ

http://www.youtube.com/watch?v=KknHVL43YJ0&feature=player_detailpage

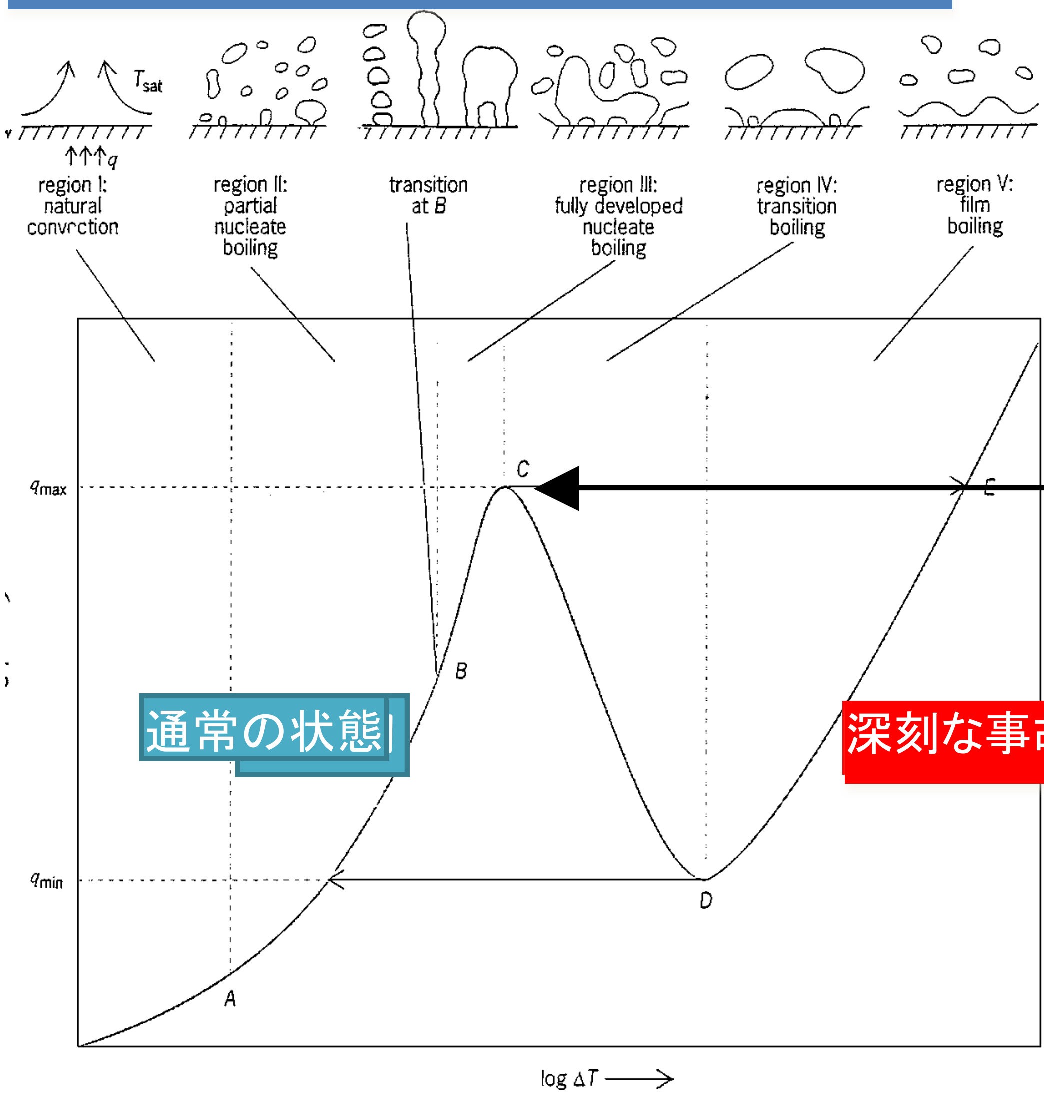
1号機水素爆発後の様子（画像：ロイター）
建屋の上部コンクリート部分が破損され鋼鉄の骨組みのみが残されている



Reuters

Loss of coolant drives up fuel pin temperature

冷却剤喪失のため燃料棒温度が上昇



通常の状態

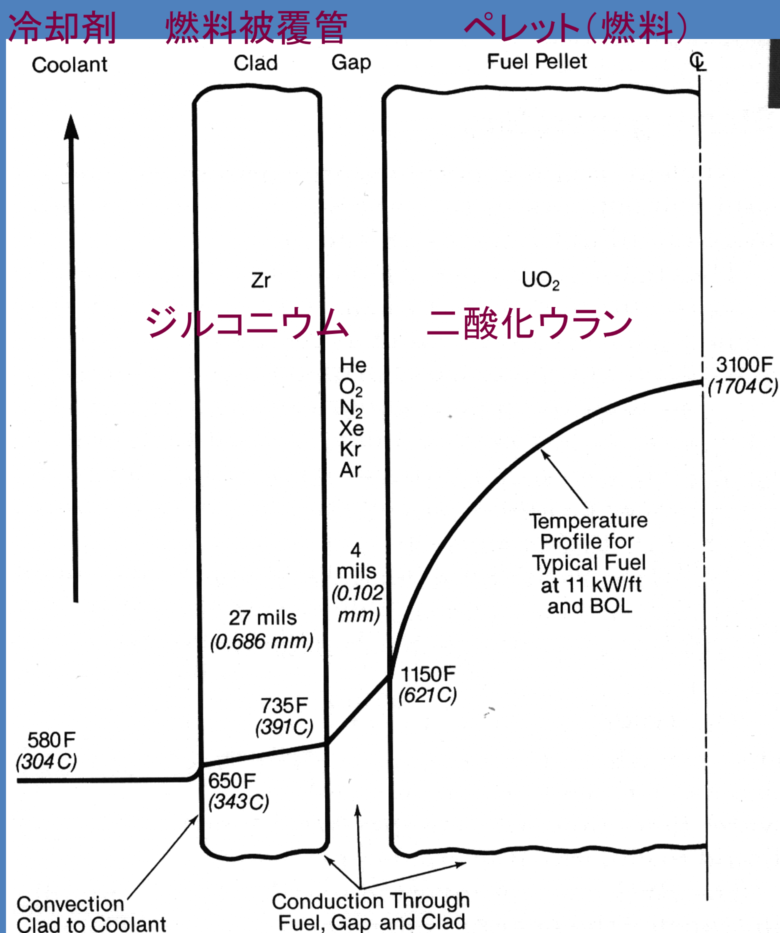
深刻な事故

限界熱量を超えると燃料棒が水蒸気に囲まれ除熱がうまくいかずに温度が急上昇→深刻な事故

Critical Heat Flux
限界熱量

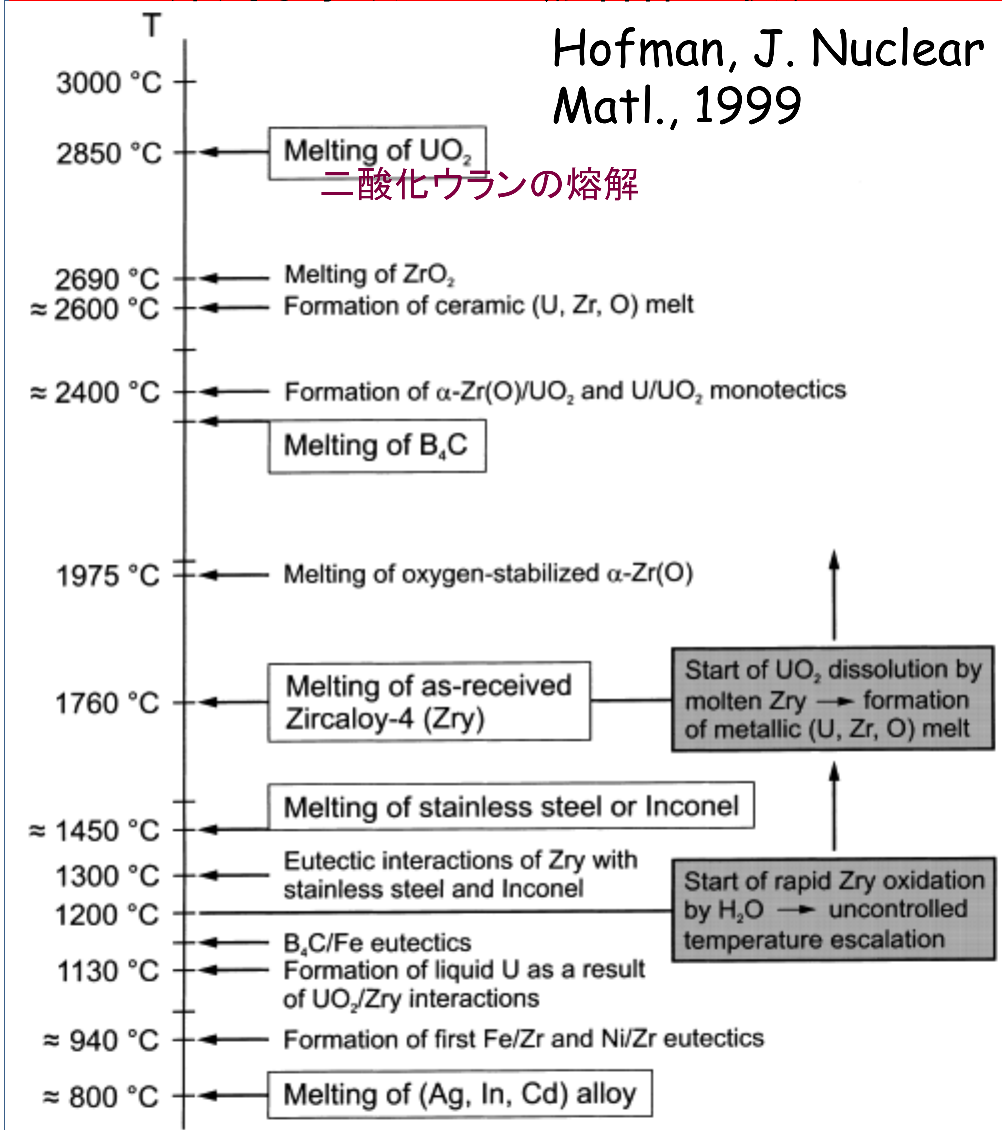
Dhir Ann Rev Fluid Mech 1998

NORMAL CONDITIONS
通常の状況下での燃料棒



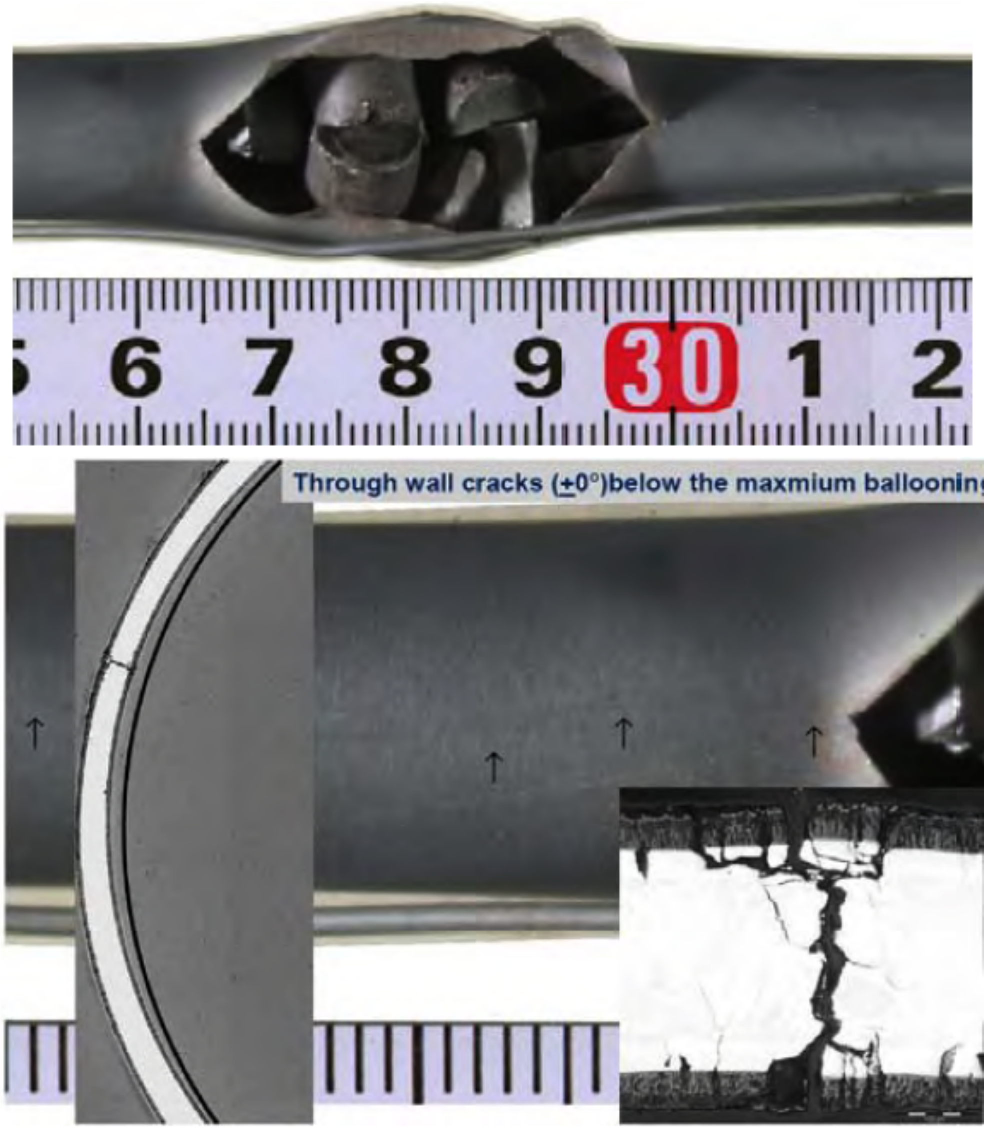
Steam – Its generation and uses, 41rst Ed Babcock - Wilcox

SEVERE ACCIDENT CONDITIONS
深刻な事故下での燃料棒の状況



Hofman, J. Nuclear Matl., 1999

ジルコニウム燃料被覆管の破裂(温度900℃以上)
Cracking and Rupture of Zr Clad



Peak cladding temperature of 900 C.

Internal pressure of FP gases creates hoop stress on clad.

Creep strength drops rapidly after 700 C.

Strains up to 50% result in:

Ballooning and relocation of fuel.

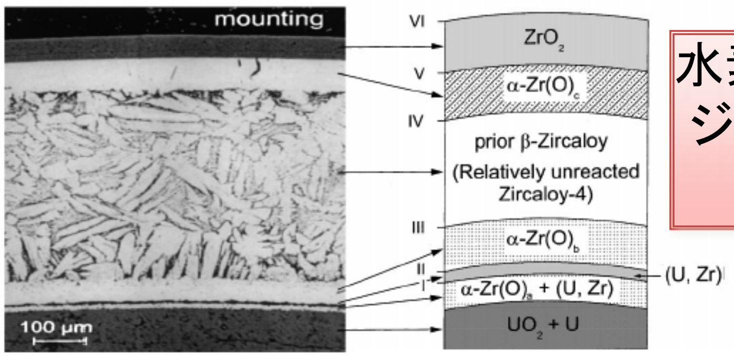
Through wall cracks.

Rupture of cladding → releasing FP gases and fuel

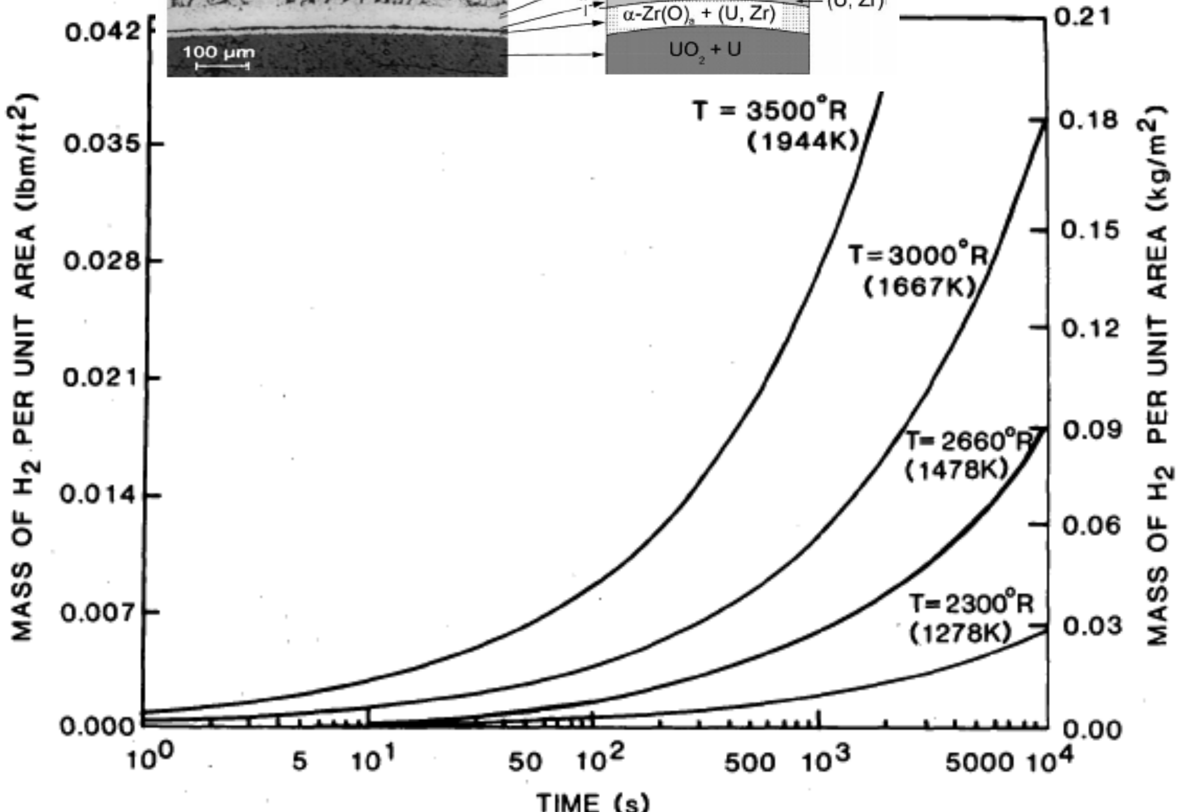
NEA 6846 2009

ジルコニウム被覆管が水蒸気と反応し水素が発生（温度1200℃以上）

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$



水素発生はエネルギー生成を伴う:
ジルコニウム1kg あたり14.6 MJの熱が発生

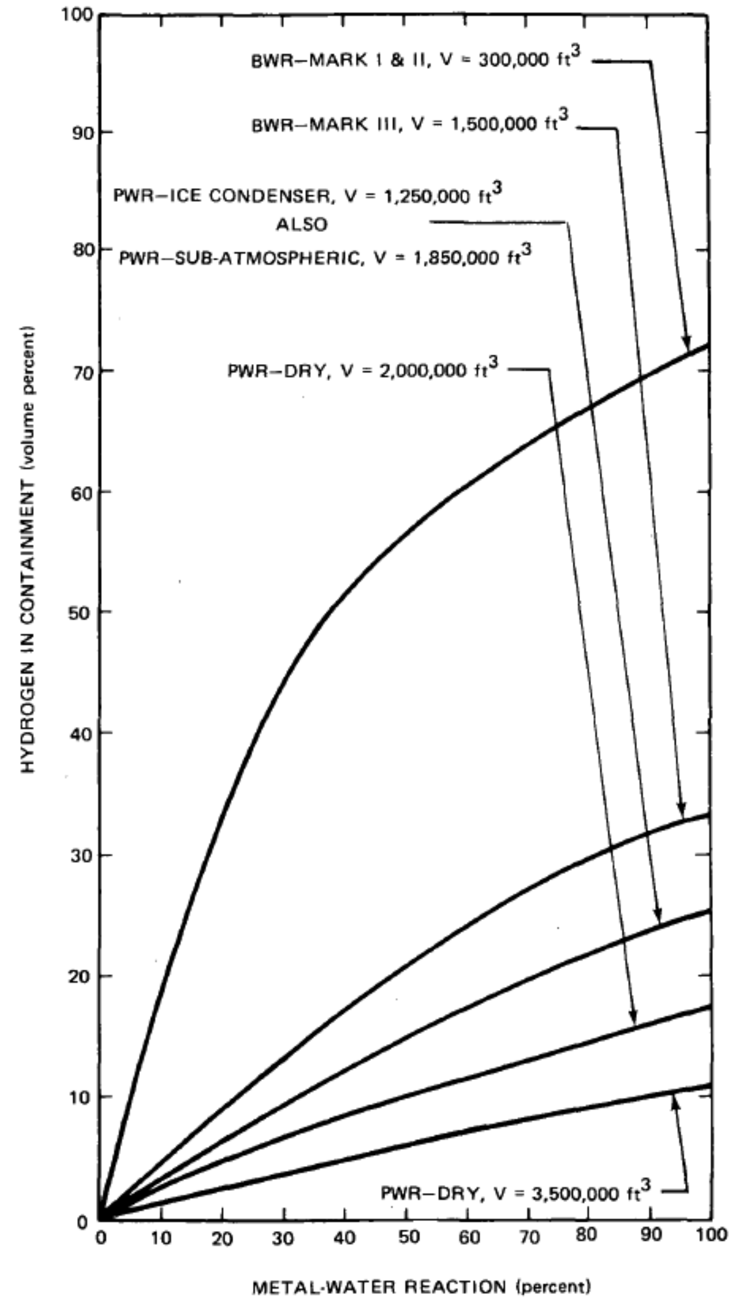


LWR H2 Manual NUREG/CR-2726

900°C	Rupture cladding
1200°C	H2 generation
1800°C	Melt clad, melt steel
2500°C	Break fuel rods, debris bed
2700°C	Zr-U eutectics

格納容器のサイズ
Containment Size

福島第一原発に使われているのはマーク1型という初期の沸騰水型原子炉であり、これは格納容器の中では最小のサイズである。そのため炉心の加熱による水素発生のリスクが高く、水素爆発を防ぐための不活性ガス（窒素）が充填されている。



LWR H2 Manual NUREG/CR-2726

Observations 観測

1 燃料棒が水から露出すると加熱が進み水素が短時間(約1時間)発生してしまう

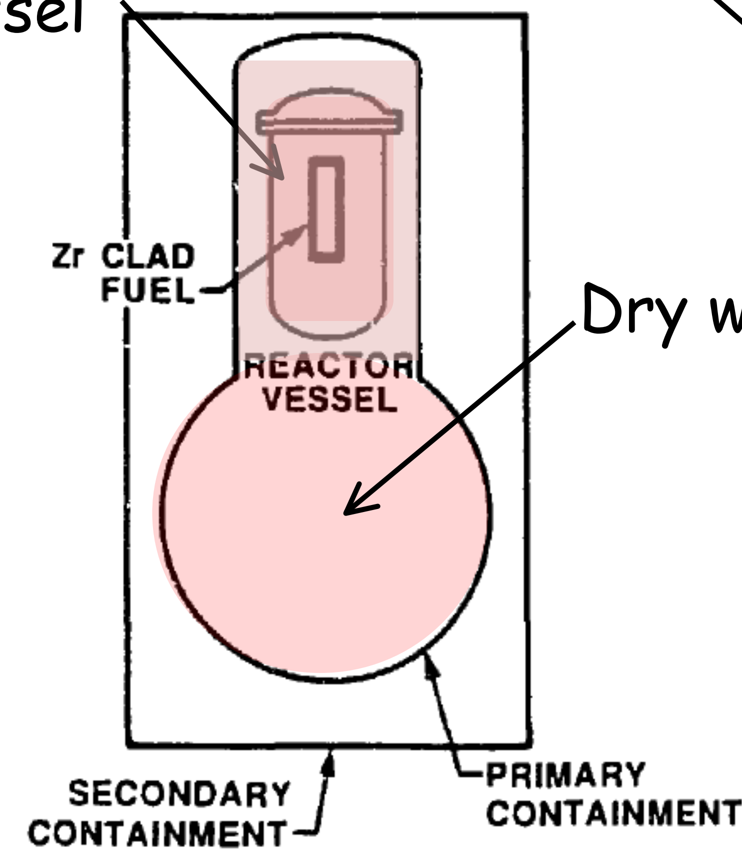
2 建屋上部の体積(2.8 x10^4 m^3)は格納容器の三倍以上の大きさだが圧力はほぼ大気圧に等しい

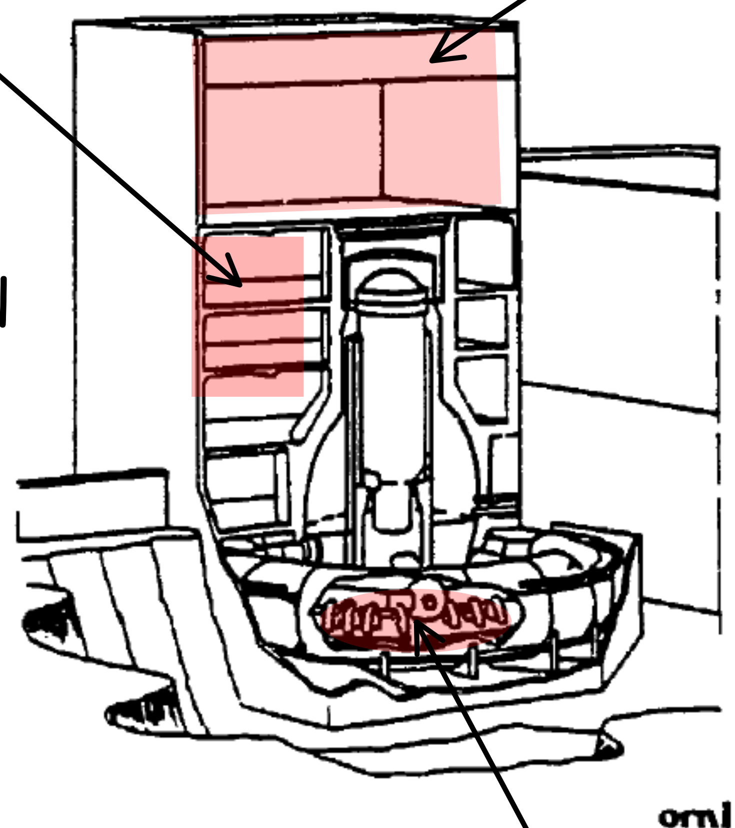
3 1ー3号機のジルコニウム被覆管の質量と予想される発生水素の質量と拡散体積(100%の反応、大気圧を仮定)。

Unit	ZR (tonne)	H2 (tonne)	H2 (m^3)
1	44	2	23804
2 or 3	60	3	32612

Where Can the H2 go?

発生した水素はどこへ行くのか？





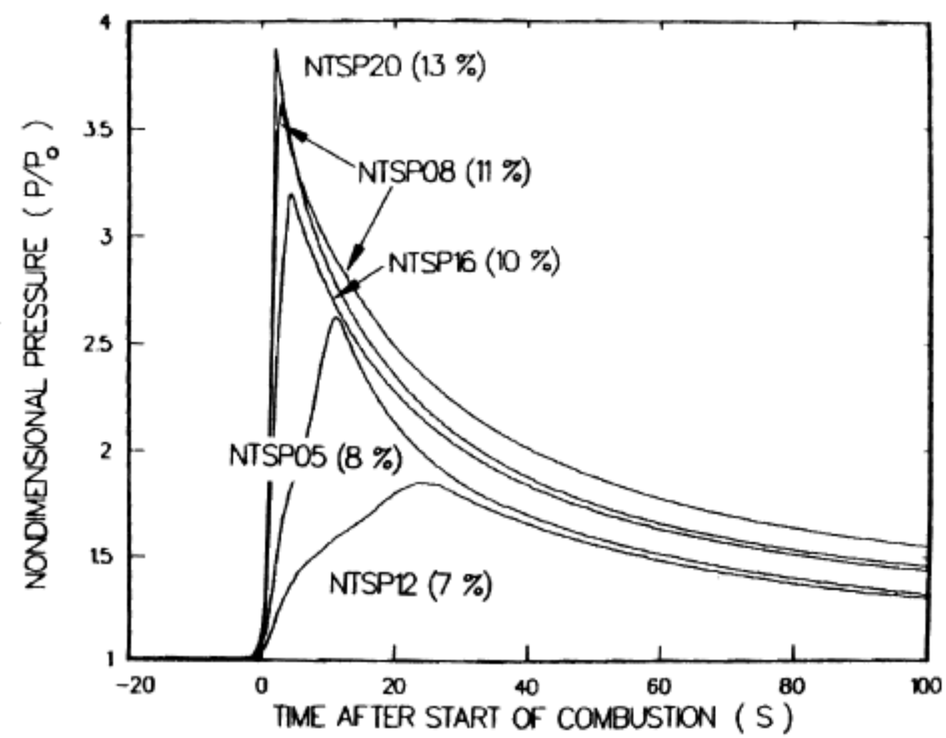
S. Greene CONF-8806153-1 ORNL

Hydrogen Combustion 水素燃焼

1. H2 +1/2 O2 (+N2 & H2O) → H2O (+N2 & H2O)
   水素分子１個あたり240 キロジュールの発熱量が発生
   水素分子1kgあたりでは120メガジュールの発熱

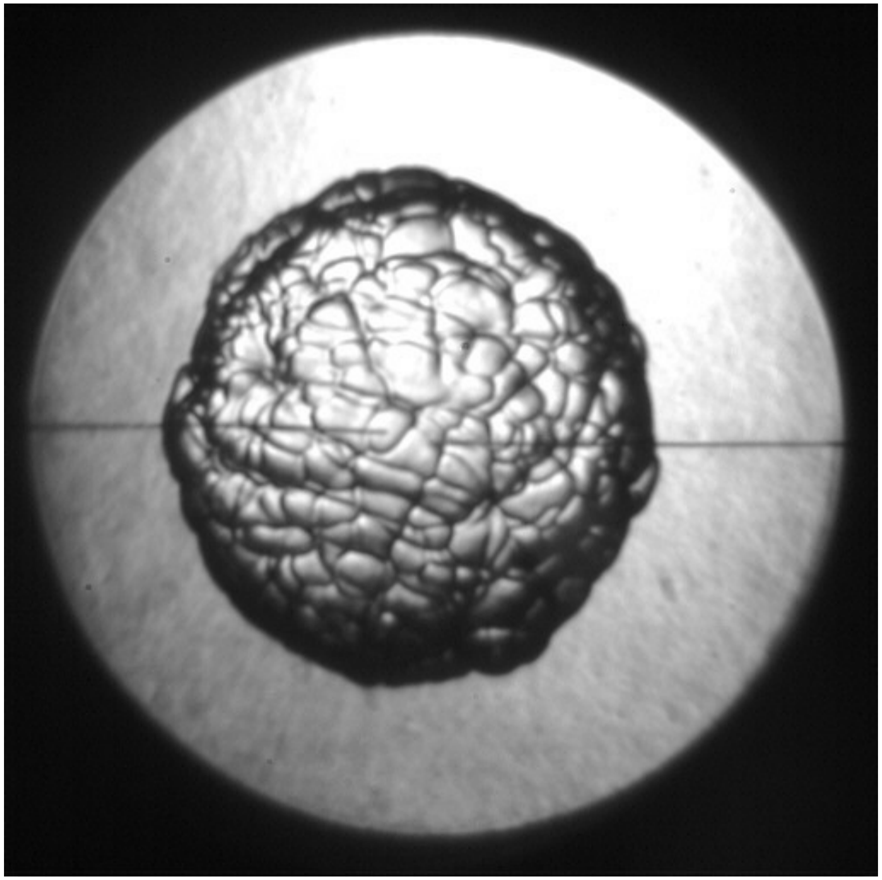
- ほとんどの発熱量（燃焼熱）は水蒸気と窒素ガスに吸収される
- 可燃性混合ガスは広い燃焼範囲（爆発範囲）を持つ
  乾燥した空気における水素の燃焼範囲は4-70%
- 簡単に引火
  スパークやアークは低エネルギーでおこる
  一千℃以上になると表面が高温になる
- 燃焼の種類
  炎 (slow 0.5 to 50 m/s)
  高速炎 (50-500 m/s)
  爆轟(1500-3000 m/s)

NUREG/CR-4138 Ratzel 1986

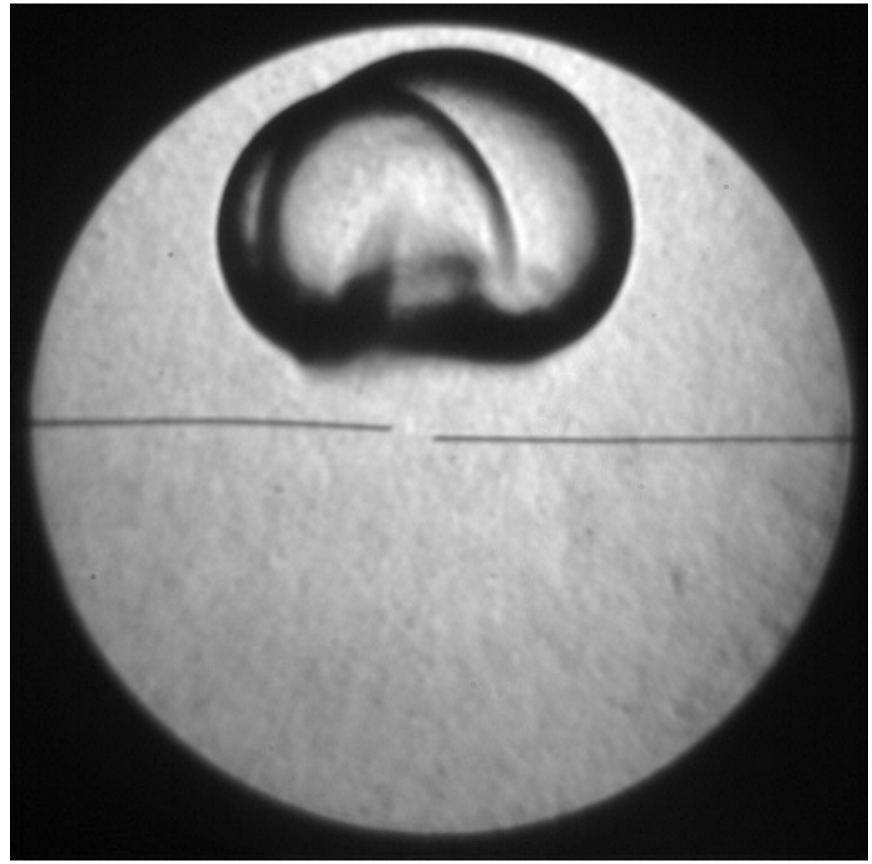


Hydrogen Flames

水素爆発（カリフォルニア工科大 での実験）



10% H2 in O_2/Ar



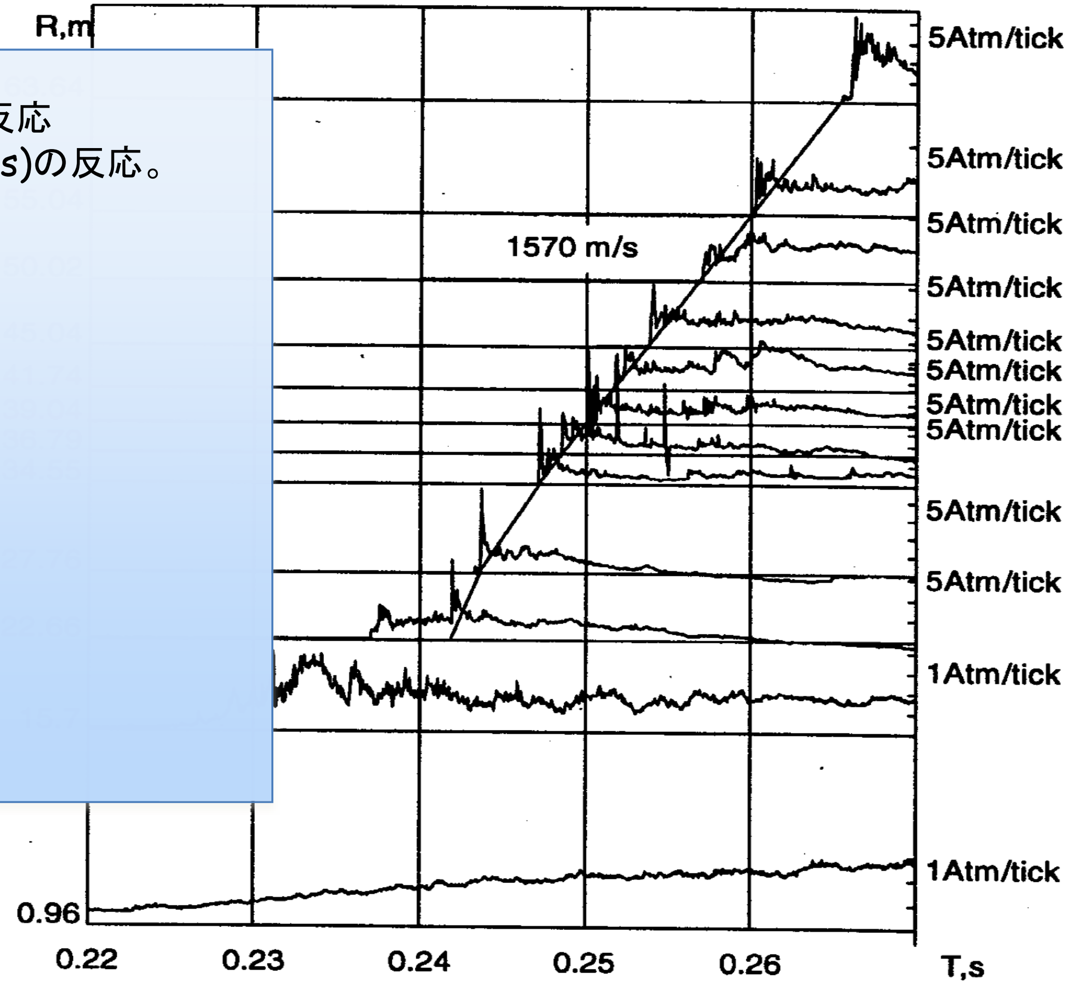
5% H2 in O_2/Ar

SPM Bane – Caltech Explosion Dynamics Lab 2010

水素燃焼ー爆燃か爆轟か？
Deflagration or Detonation?

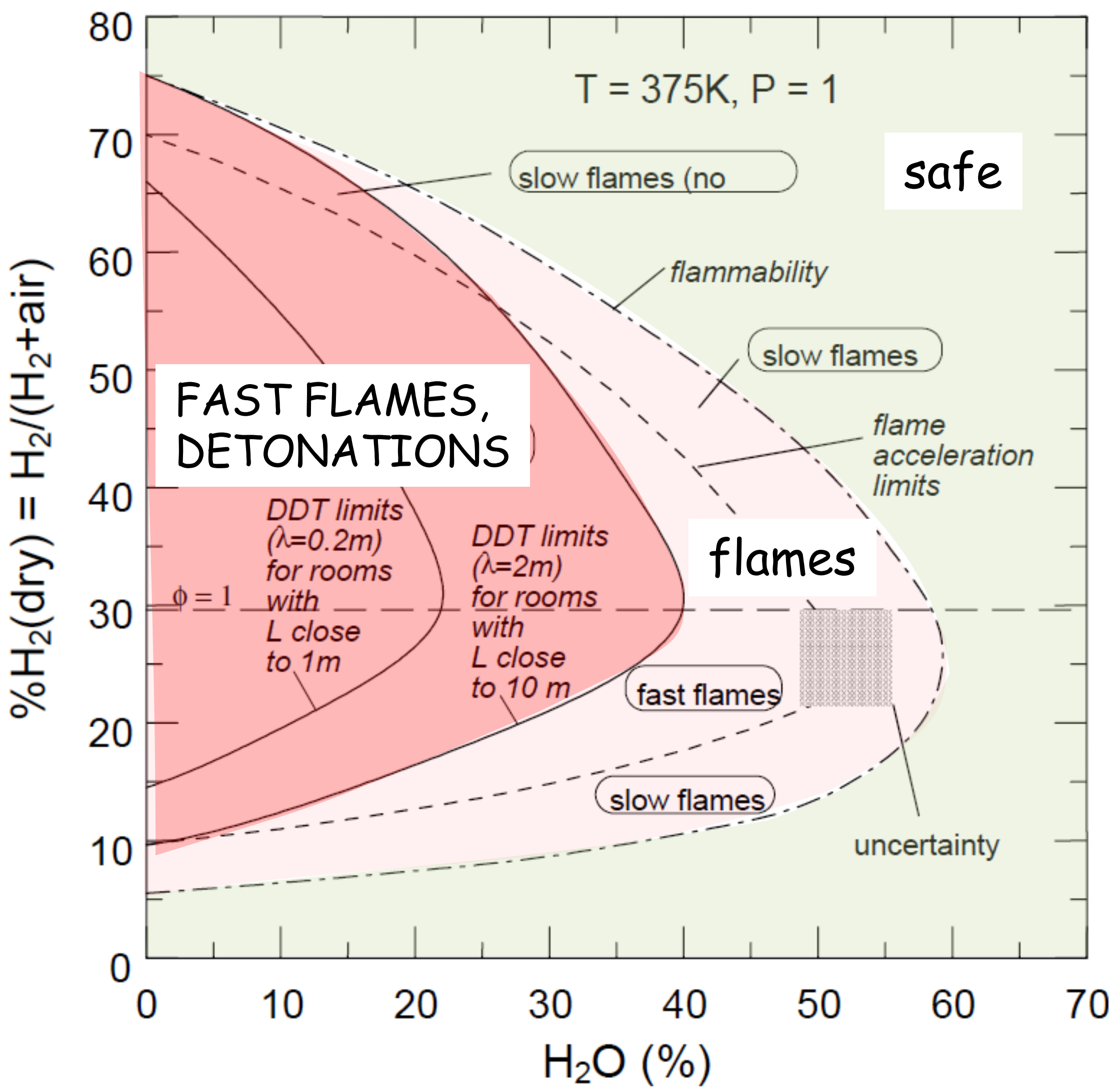
1. 水素燃焼のモード
   1. 爆燃(deflagration)→低速度(5-100m/s)の反応
   2. 爆轟 (detonation) →高速度(1500-2500m/s)の反応。衝撃波を伴う
   3. 爆燃から爆轟への変移も起こりうる
2. 圧力上昇は以下の要素に依存
   1. ガスの組成 （例えば水素ガスや水蒸気の量）
   2. 温度と圧力
   3. 燃焼のモード
   4. 弁と容器の損傷具合

4. Venting or failure of structures



18% H2 (dry) 15% steam RUT (60 x 2.5 x 2.5 m) Dorofeev 1995

水素-空気-水蒸気の混合物における燃焼様式

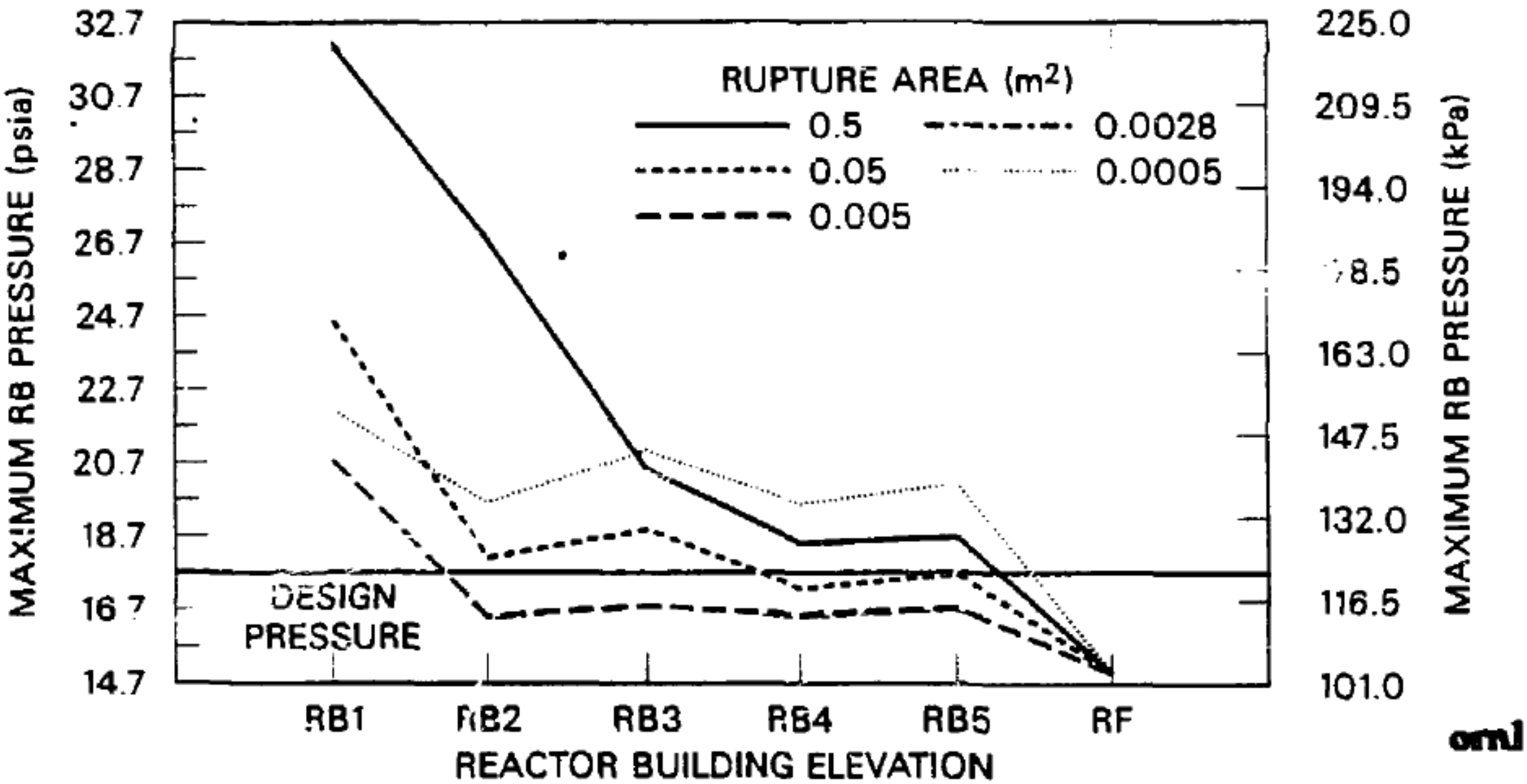


OECD NEA/CSNI/R(2000)7

Extensive research programs in USA, Europe, Japan, FSU from 1980-2000 on H2-air-steam. Motivation was TMI accident and follow-on studies.

Programs in Japan, Germany on H2-O2-steam after 2001 pipe ruptures in Hamaoka Unit 1 and Brunsbüttel.

格納容器の耐圧性能



S. Greene CONF-8806153-1 ORNL

1号機の状況(3/12-13)

- 発電所の停電から24時間後に爆発。最初のベントの5.5時間後
- 最初の爆発はおもに横向きで、目に見える破損物が100m以上の高さまで飛んだ。
- デザインから予測されるように燃料補給部周囲のパネルが吹き飛ぶ
- 建物の骨格はほぼ無傷
- 原子炉部の破損状況は不明
- 発生した雲は主にゴミやコンクリートのようだ
  - 核分裂生成物質の放出量はベントよりも同量か少ないように見受けられる(下の公表値参照)
- 原子炉圧力容器と原子炉格納容器は圧を保ったようだ(4/3測定値参照)
- 爆発は亜音速であったようだ
  - Relatively low concentration <10-15%) of H2 at time of explosion so DDT did not occur.

3号機で電源喪失

Sunday, March 13, 2011				
	2:00:00	13.08	35.20	Seawater injection into unit 1 in progress.
	2:44:00	13.11	35.93	Batteries fail in Unit 3
	5:30:00	13.23	38.70	Containment integrity in Unit 1 verified
	6:23:00	13.27	39.58	RCICS fails in Unit 3.
	8:41:00	13.36	41.88	Controlled venting in Unit 3. Fuel exposed up to 3 m.
	8:56:00	13.37	42.13	Radiation dose at site boundary MP4 exceeds limit value.
		13.39	42.56	0.28 mSv/hr spike at front gate MP
	11:00:00	13.46	44.20	Starting to vent Unit 2
	11:55:00	13.50	45.12	Fresh water injection into Unit 3 through fire line in progress.
	13:12:00	13.55	46.40	Sea water injection into Unit 3 through fire lines in progress.
	14:00:00	13.58	47.20	RCICS working for Unit 2.
	14:15:00	13.59	47.45	Radiation dose at site boundary MP4 exceeds limit value.
		13.60	47.60	0.06 mSv/hr spike at front gate MP
	15:38:00	13.65	48.83	Warning of H2 explosion in unit 3

Monday, March 14, 2011				
	1:10:00	14.05	58.37	Injection to Units 1 and 3 halted - ran out of water in pit. Unit 1 injection "temporarily interrupted" - not clear when this was restarted.
		14.10	59.60	0.75 mSv/hr spike at front gate MP
	3:20:00	14.14	60.53	Injection to Unit 3 restarted.
	3:50:00	14.16	61.03	Radiation dose at site boundary MP6 exceeds limit value.
	4:08:00	14.17	61.33	Temperature up to 84 C in Unit 4 spent fuel pool
	4:15:00	14.18	61.45	Radiation dose at site boundary MP2 exceeds limit value.
	5:20:00	14.22	62.53	Starting to vent Unit 3.
	7:44:00	14.32	64.93	Pressure rise in PCV of Unit 3.
	7:52:00	14.33	65.07	Article 15 emergency notification.
	9:27:00	14.39	66.65	Radiation dose at site boundary around MP3 exceeds limit value.
	9:37:00	14.40	66.82	Radiation dose at site boundary around main entrance exceeds limit value.
3号機水素爆発	11:01:00	14.46	68.22	Explosion destroys Unit 3 refueling bay superstructure, panels, extensive damage. Visible flash at beginning of explosion. Large dark cloud at least 500 m high, fragments possibly impact unit 2 and 4 reactor buildings. 11 workers injured.
	11:01:00	14.46	68.22	Blowout panel in unit 2 reactor building opened up following unit 3 explosion.
		14.48	68.72	0.05 mSv/hr spike at front gate MP
	13:18:00	14.55	70.50	Water level in unit 2 RPV falling.
2号機　原子炉隔離時冷却系ストップ 3号機の爆発の2次的影響？			70.62	RCICS fails for Unit 2. Potentially caused by secondary effects of explosion in Unit 3.
			71.02	Article 15 emergency notification for Unit 2.
			76.53	Seawater injection by fire line prepared for Unit 2 RPV. Difficulty in injection apparently due to not being able to open pressure relief valves.
	20:33:00	14.86	77.75	Seawater injection by fire line for Unit 2 RPV. NISA has this happening at 16:34
		14.90	78.80	3.13 mSv/hr spike at front gate MP
	22:50:00	14.95	80.03	Water level in unit 2 RPV falling. Rise of pressure in PCV.

3号機での水素爆発

http://www.guardian.co.uk/world/video/2011/mar/14/fukushima-nuclear-plant-reactor-explosion-video

3号機

March 17 – Tepco

上空写真（2011年3月14日）

NY Times – DigitalGlobe

3号機の状況

- 電源喪失の32時間後、ベントの6時間後に爆発
- 目で見える炎の発生
  - Occurs as panels blow out, probably luminosity from entrained debris
- 300-500m以上、ものが飛びあがる
- 50km以上の距離から音が聞こえていた
- パネルや骨格は外向きに吹き出され、屋根は下に落ちる
  - Debris in pool – not clear where crane structure is now located
  - Damage to turbine building roof may be associated with building fragments or equipment hurled out of refueling bay
- Concrete beams and panels below refueling deck damaged
- 原子炉圧力容器と原子炉格納容器は圧を下げている（4/9現在）

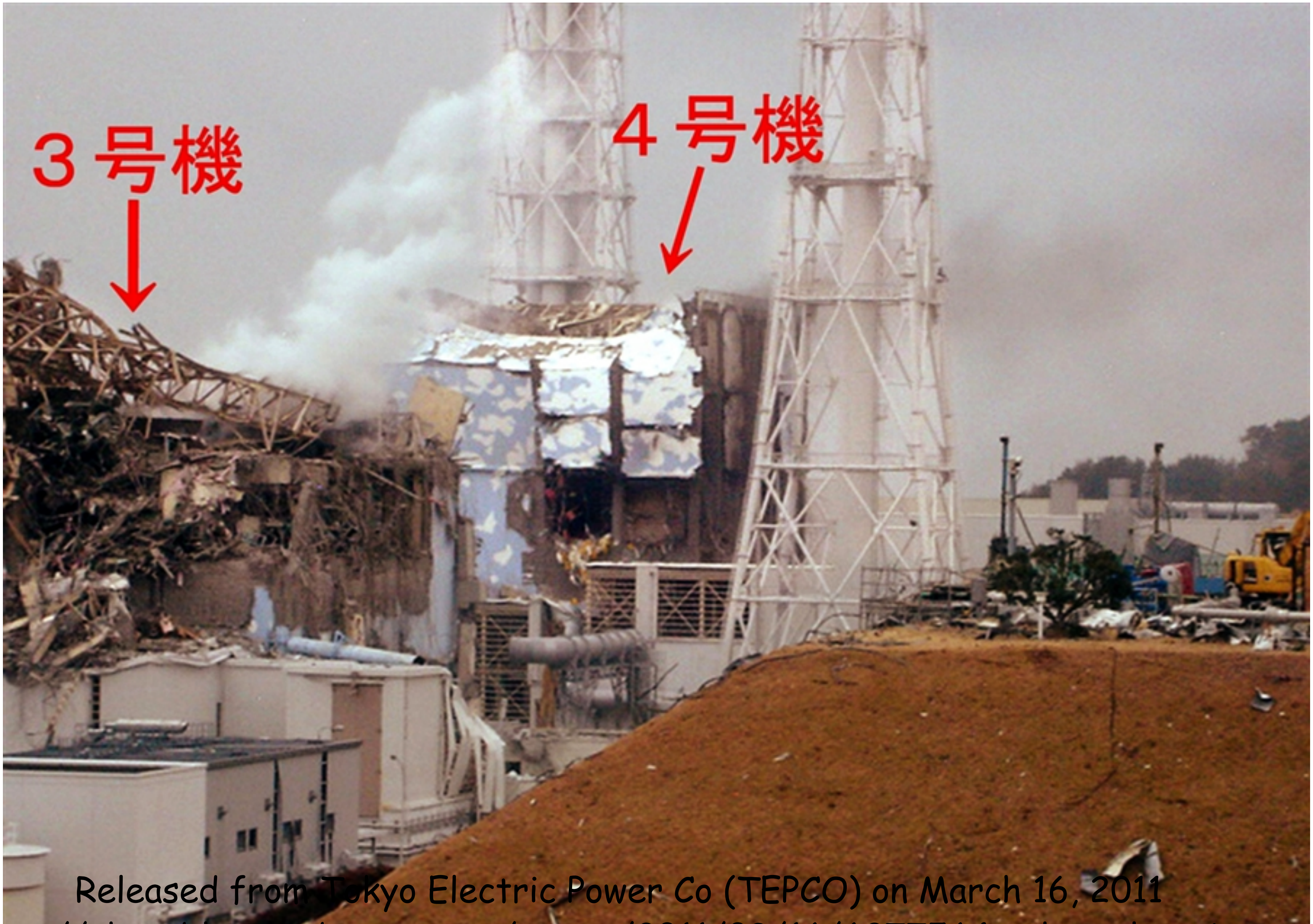
Tuesday, March 15, 2011				
	0:02:00	15.00	81.23	Starting to vent Unit 2
	6:00:00	15.25	87.20	Explosive sound and fire near 5th floor of Unit 4 .
	6:10:00	15.26	87.37	Pressure drop in suppression torus in Unit 2
	6:14:00	15.26	87.43	Damage to reactor wall in operation area confirmed for Unit 4
	6:20:00	15.26	87.53	Explosive sound near torus in Unit 2.
		15.00	81.20	All personnel evacuated and only 50 remain to operate plant.
	6:51:00	15.29	88.05	Radiation dose at site boundary around main entrance exceeds limit value.
	8:11:00	15.34	89.38	Radiation dose at site boundary around main entrance exceeds limit value.
		15.38	90.32	11.9 mSv/hr spike at front gate MP
	9:38:00	15.40	90.83	Explosion followed by fire in Unit 4
	10:00:00	15.42	91.20	Radiation dose on 400 mSv/h on inland side of Unit 3 and 100 mSv/h on inland side of Unit 4.
	11:00:00	15.46	92.20	Fire in Unit 4 reported to spontaneously extinguish.
	12:00:00	15.50	93.20	Large release starts and continues into Wednesday.
	16:17:00	15.68	97.48	Radiation dose at site boundary around main entrance exceeds limit value.
	23:05:00	15.96	104.28	Radiation dose at site boundary around main entrance exceeds limit value.
		15.98	104.72	8.08 mSv/hr spike at front gate MP

２号機の状況

- 原子炉隔離冷却系の喪失から17時間後に爆発。ベントされたか不明
- ２号機／４号機の爆発／火事はほぼ同時期に発生
  - 建物やベントの共通部から？
  - 偶然の一致?
- ２号機での出来事は1,3号機と大きく異なる
  - サプレッションプールのある円環部（トーラス）で爆発音がし、建物丈夫には明らかな損傷はない
  - 格納容器の圧力減少が先立った
  - どこかしら格納容器の損傷があった？？
- 起こったこと(あくまで純粋な推測)
  - Small H2 explosion in torus room only (seems unlikely) and/or
  - Core melt relocation within RPV resulting in
    - Steam "spike" and/or
    - Core penetrates failed lower head and drops into water in reactor cavity
- 原子炉と格納容器の圧は爆発以来下がっている

4号機の状況

- どのように破損が起こったか不明
  - 火事 → 爆発 *もしくは* 爆発 → 火事
  - 一回の爆発それとも複数？
  - 何が燃えたか？
    - ジルコニウム合金自体?
    - 蒸気との反応で発生した水素？
    - 燃料交換部にある他の物質？
    - 冷却系からもれた水素？
- 爆発により多大な損傷
  - 多数のパネルが吹き飛んだことは相当量の水素が溜まっていたことを示す



Released from Tokyo Electric Power Co (TEPCO) on March 16, 2011
http://photoblog.msnbc.msn.com/_news/2011/03/16/6277564-tokyo-electric-power-company-released-new-images-of-damaged-nuclear-reactors

March 17, 2011 Tepco image of damage to Unit 4.

Frame from video taken on March 16 by SDF helicopter overflight. Unit 3

Frame from video taken from SDF helicopter overflight. Unit 4

Frame from video taken from SDF helicopter overflight. Unit 4

事後経過

- 地震発生, 強い揺れ, 地盤沈下およびずれ
- 敷地外電力の喪失 (送電線網の喪失)
- 津波到来
- 全ての予備ディーゼル発電機の喪失
- バッテリー予備電源のみによる装置およびバルブへの電力供給
- バッテリーの喪失
- 崩壊熱の除去 (Isolation condenser in unit 1, RCICS in unit 2, 3) の停止
- コアの, Zr 被覆の過熱および蒸気による酸化
- コアの激しい損傷, 水素発生
- 圧力の低下および水を満たす為に, 原子炉圧力容器(RPV)の排気
- 消防車によるRPVへの海水の注入および、蒸気のサプレッションプールへの排気
- 主要格納容器 – 蒸気/窒素/水素による充填
- 主要格納容器の損傷を避けるために排気
- 原子炉建屋の、発火の恐れのある水素, 空気, および蒸気の混合物による充満
- 水素爆発による建屋の壁の損傷 – 核融合による生成物の大気への放出ルートが生成 – により粒子が大気中に放出

使用済み核燃料棒プール

福島第一原発における冷却プール内の燃料棒の数

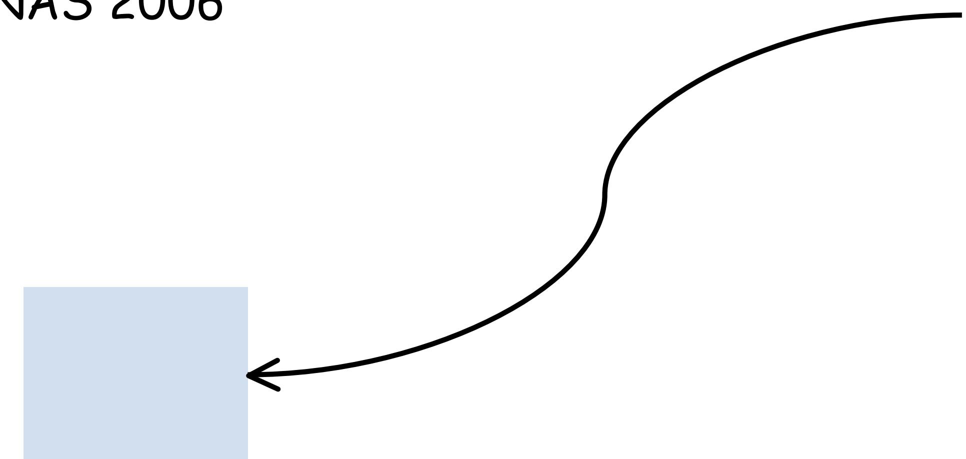
(Reported 17 March by Japan's Ministry of Economy, Trade and Industry)

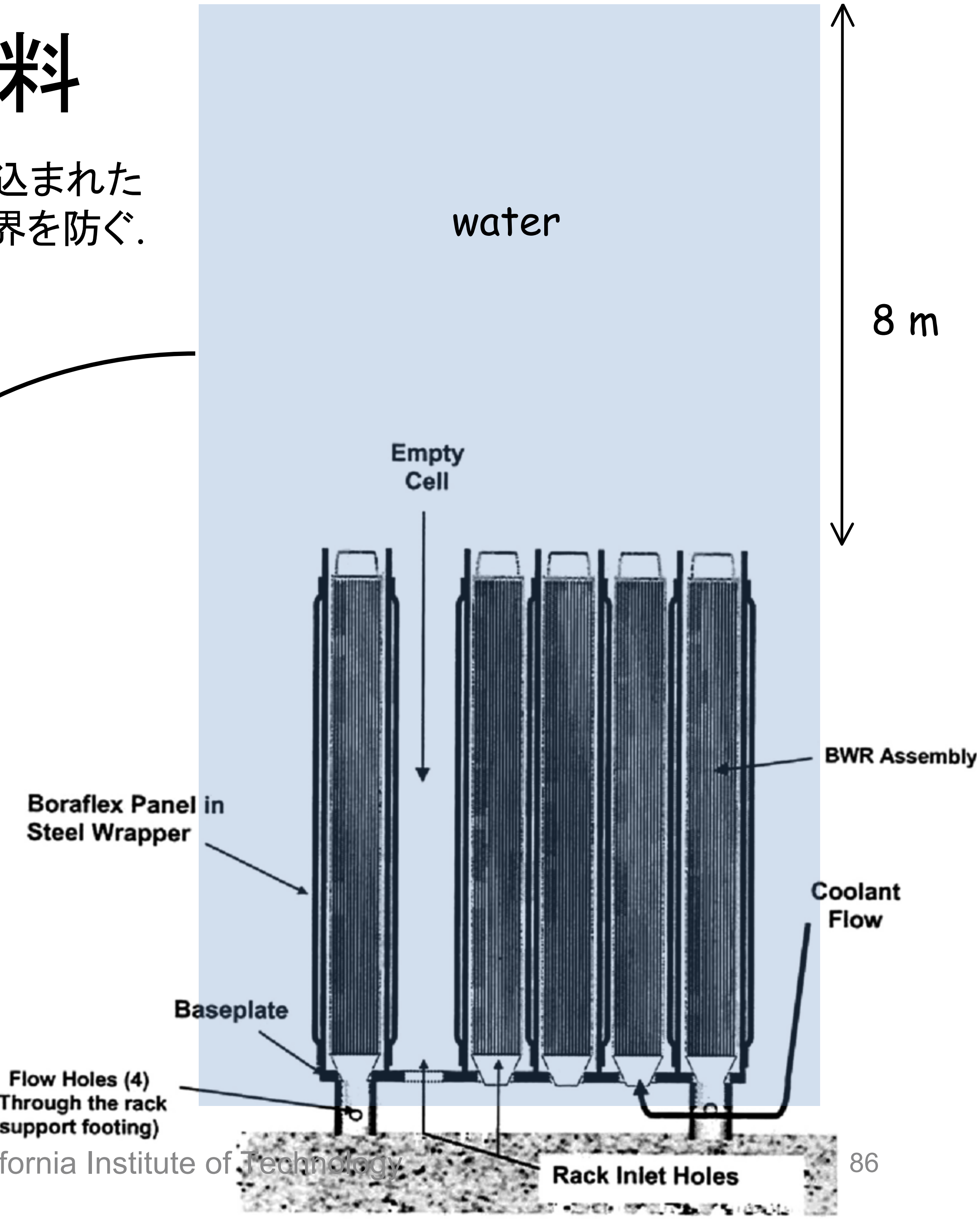
	Capacity	Irradiated Fuel Assemblies	Unirradiated Fuel Assemblies	Most Recent Additions of Irradiated Fuel
Unit 1	900	292	100	Mar-10
Unit 2	1,240	587	28	Sep-10
Unit 3	1,220	514	52	Jun-10
Unit 4	1,590	1,331	204	Nov-10
Unit 5	1,590	946	48	Jan-11
Unit 6	1,770	876	64	Aug-10

使用済み核燃料

Boraflex™ - ポリメチル基盤に埋め込まれた炭化ホウ素が中性子を吸収し、再臨界を防ぐ.

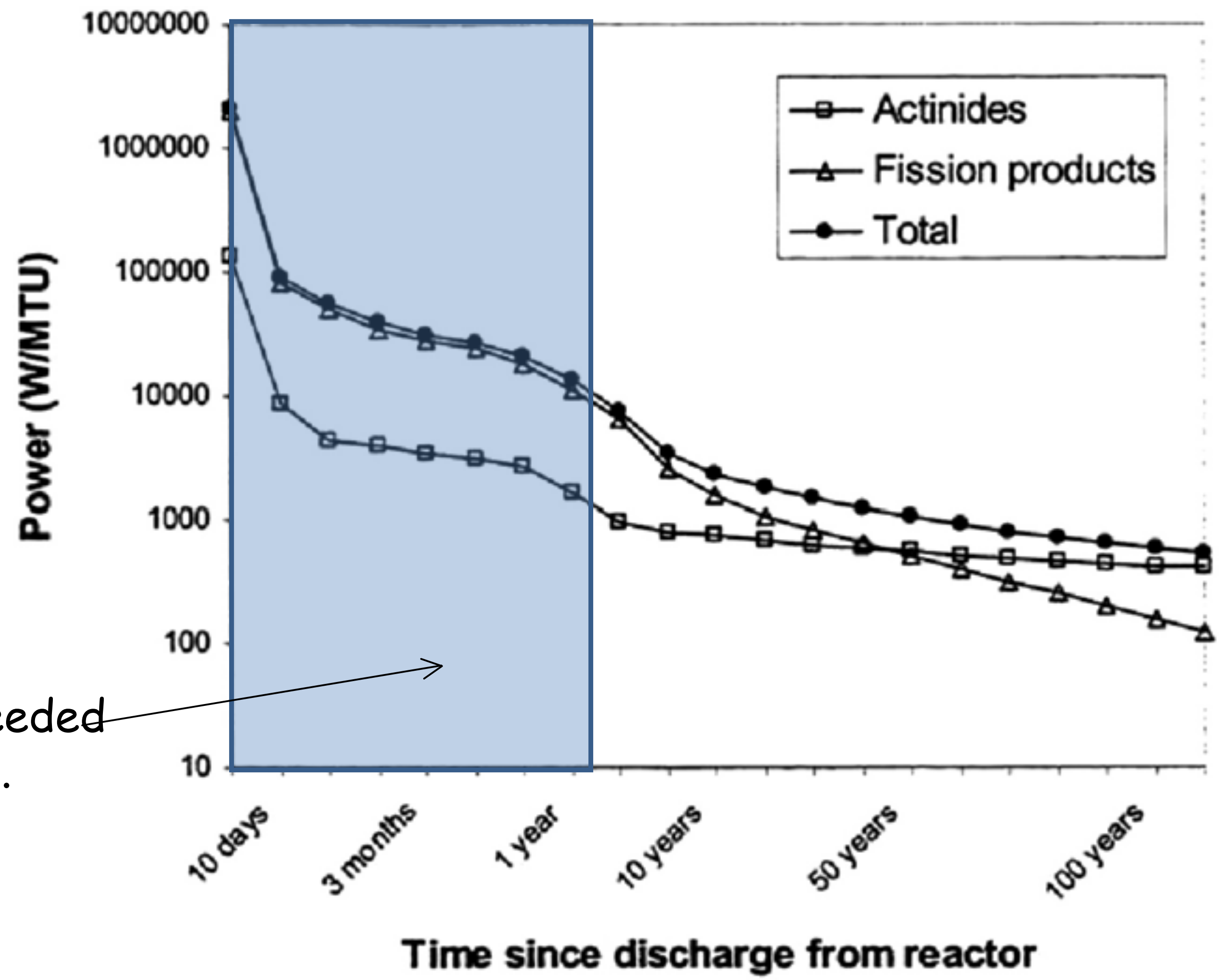
NAS 2006





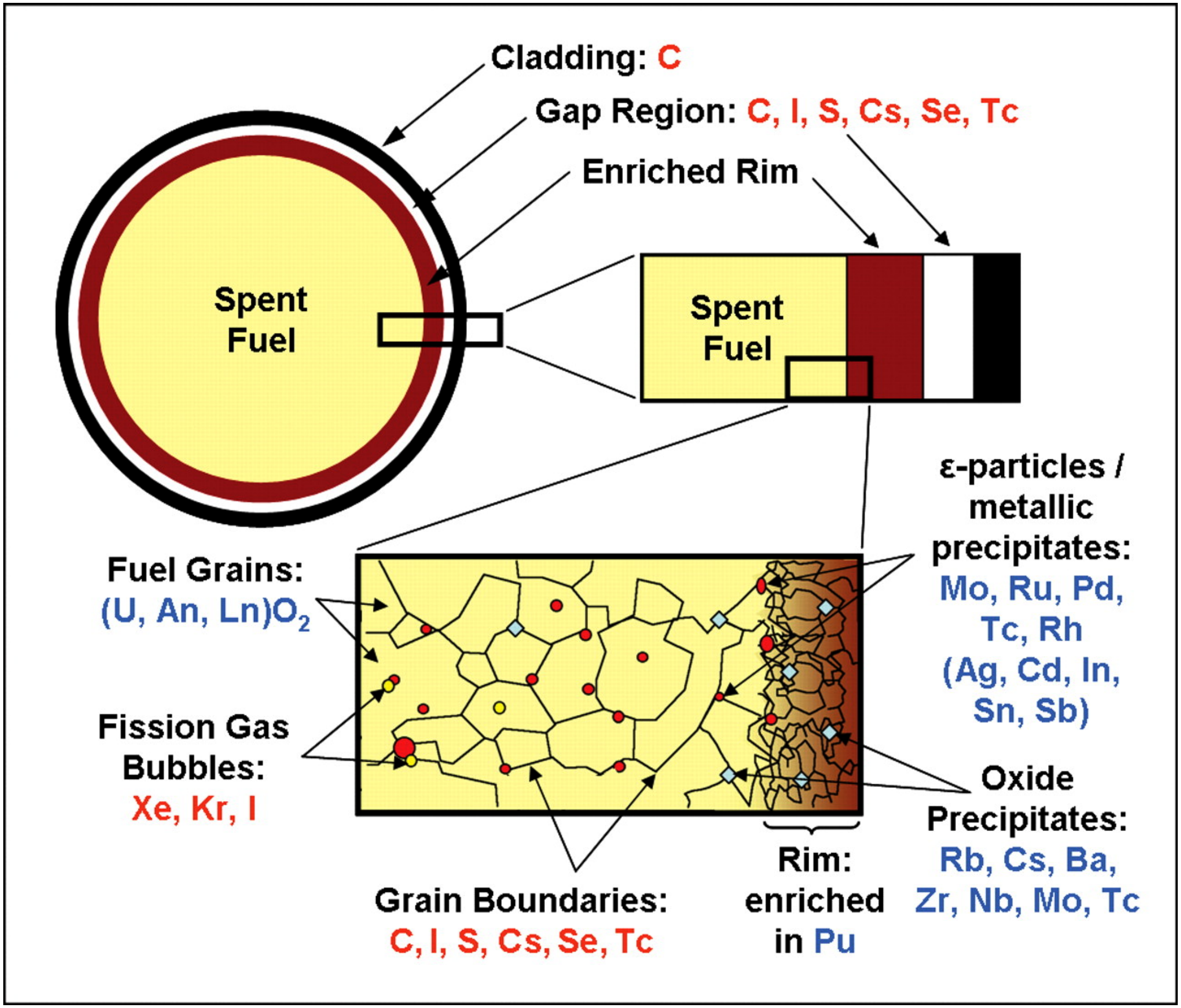
崩壊熱

Actinides are U, Pu, Np, Am



Active cooling needed for first 3 years.

Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report http://www.nap.edu/catalog/11263.html



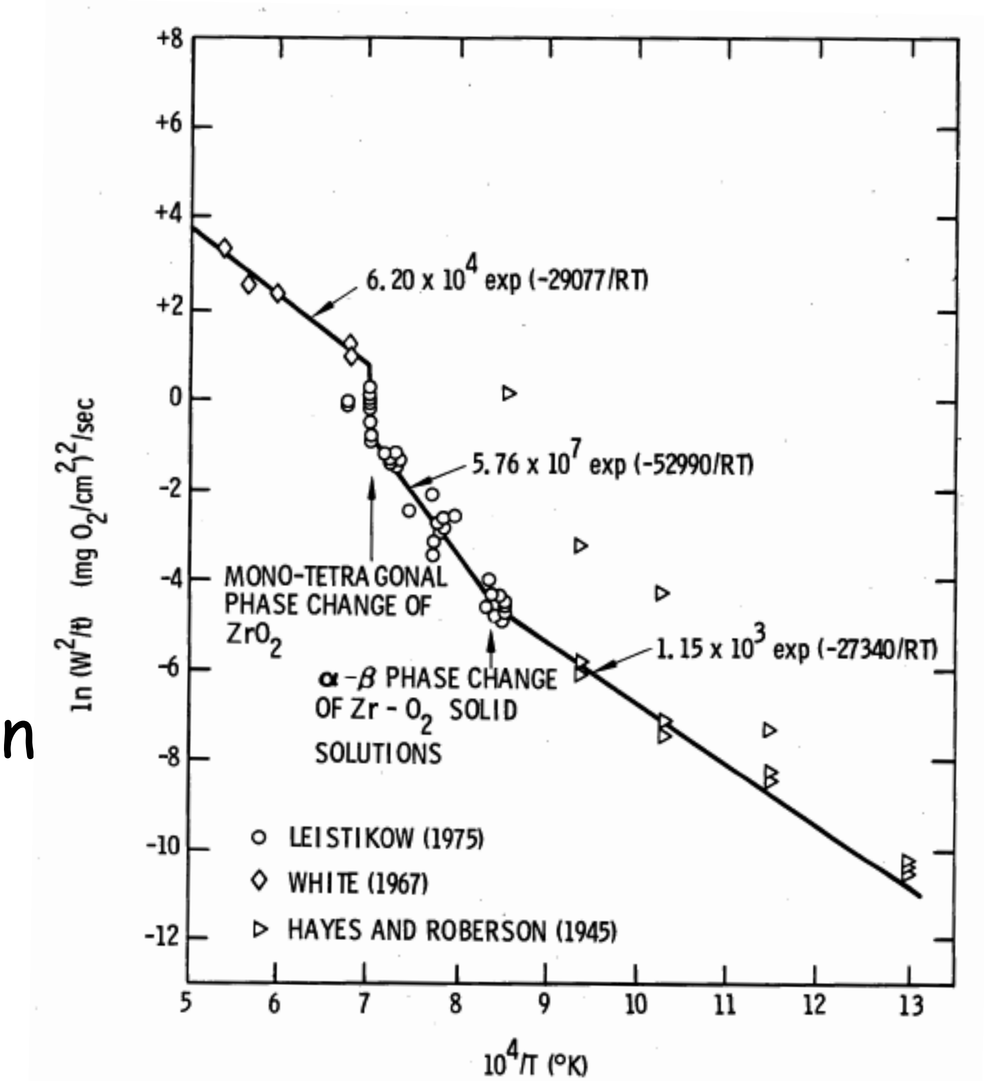
Elements; December 2006; v. 2; no. 6; p. 343-349; DOI: 10.2113/gselements.2.6.343

ジルコニウム合金の空気による酸化

- $Zr + O_2 \rightarrow ZrO_2$
- +1260 kJ/mole Zr
- Parabolic rate law

$$\frac{d}{dt}m^2 = K_o \exp(-E_a/RT)$$

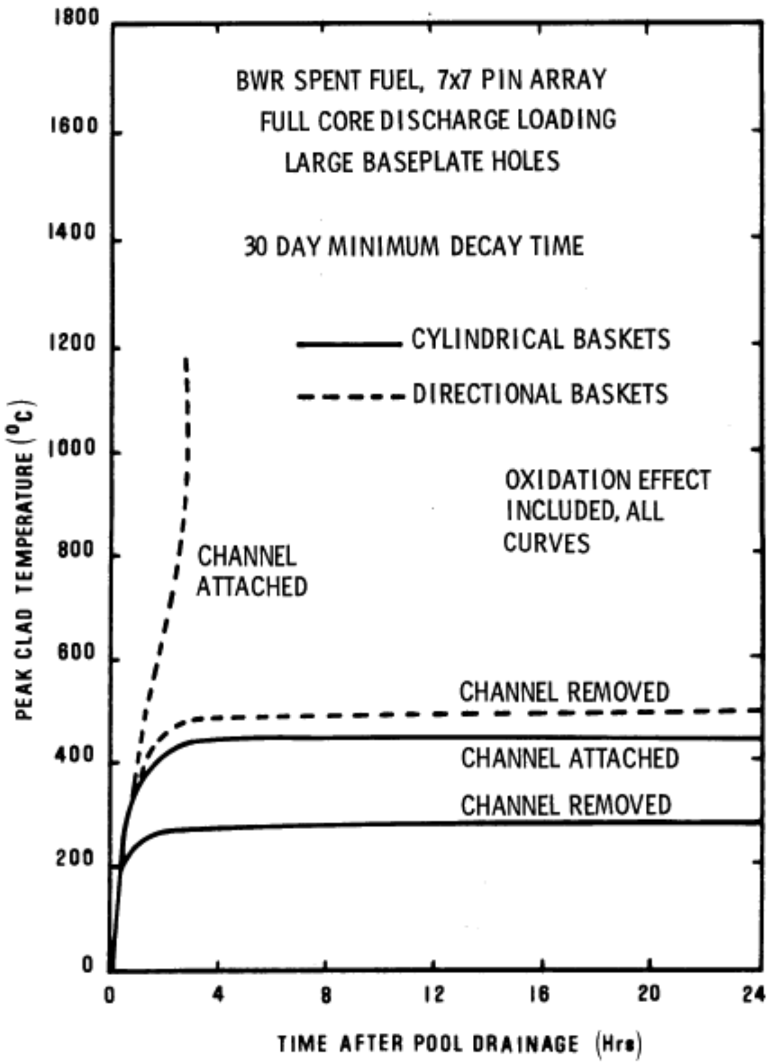
- *m* = mass of O_2/area
- Diffusion-controlled if starved for O2
- Decay heat and oxidation heating cause cladding failure (rupture) at 850 – 950 C.



NUREG/CR-0649 Spent Fuel Heatup Following Loss of Water During Storage

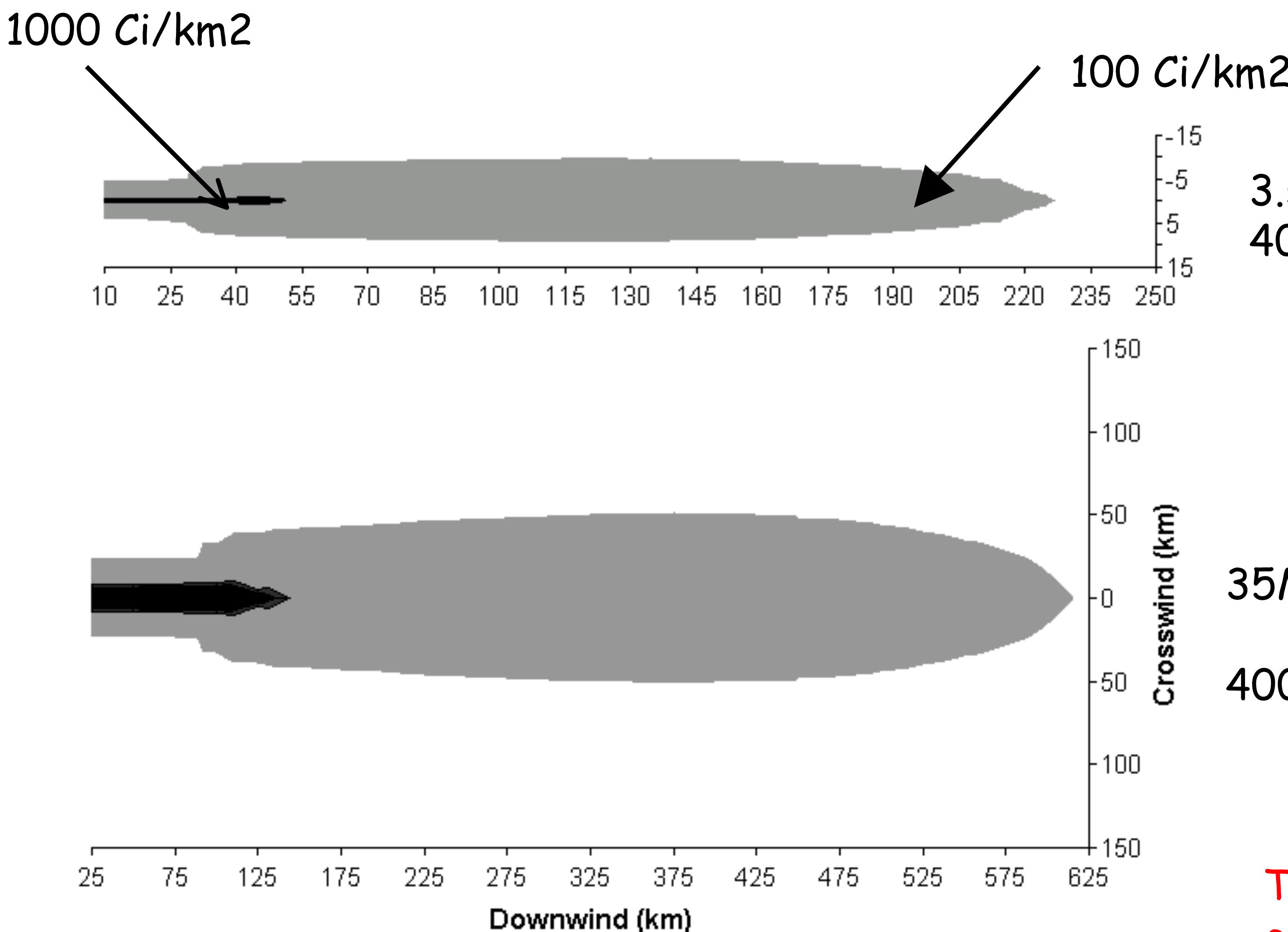
使用済み核燃料プールの水喪失によりおこる事故

- 要因
  - 核燃料棒複合体の密度／デザイン
  - 半減期
  - 換気状態
- 不完全な排水
  - 自然対流が止まる
  - 温度があがる？
- 放水
  - 少量でも効果あり(100 gal/min)



NUREG/CR-0649 Spent Fuel Heatup Following Loss of Water During Storage

使用済み核燃料棒からのセシウム137の散布



3.5MCi total
40 tonne spent fuel

35MCi total

400 tonne spent fuel

These results are controversial!

Alvarez et al Science and Global Security 11,1-51, 2003

使用済み核燃料棒プールについての考察

- 原子炉の冷却と同様にプールの冷却も重要
- 2724 燃料棒, 合計 470 MTHMに対応.
- 使用済み核燃料の総量のほぼ半分を格納している4号建屋に強い懸念.
- 揺れ, 燃料交換用の取り外し可能扉の損傷, 建屋の損傷により, 初期段階に冷却水が失われていた可能性.

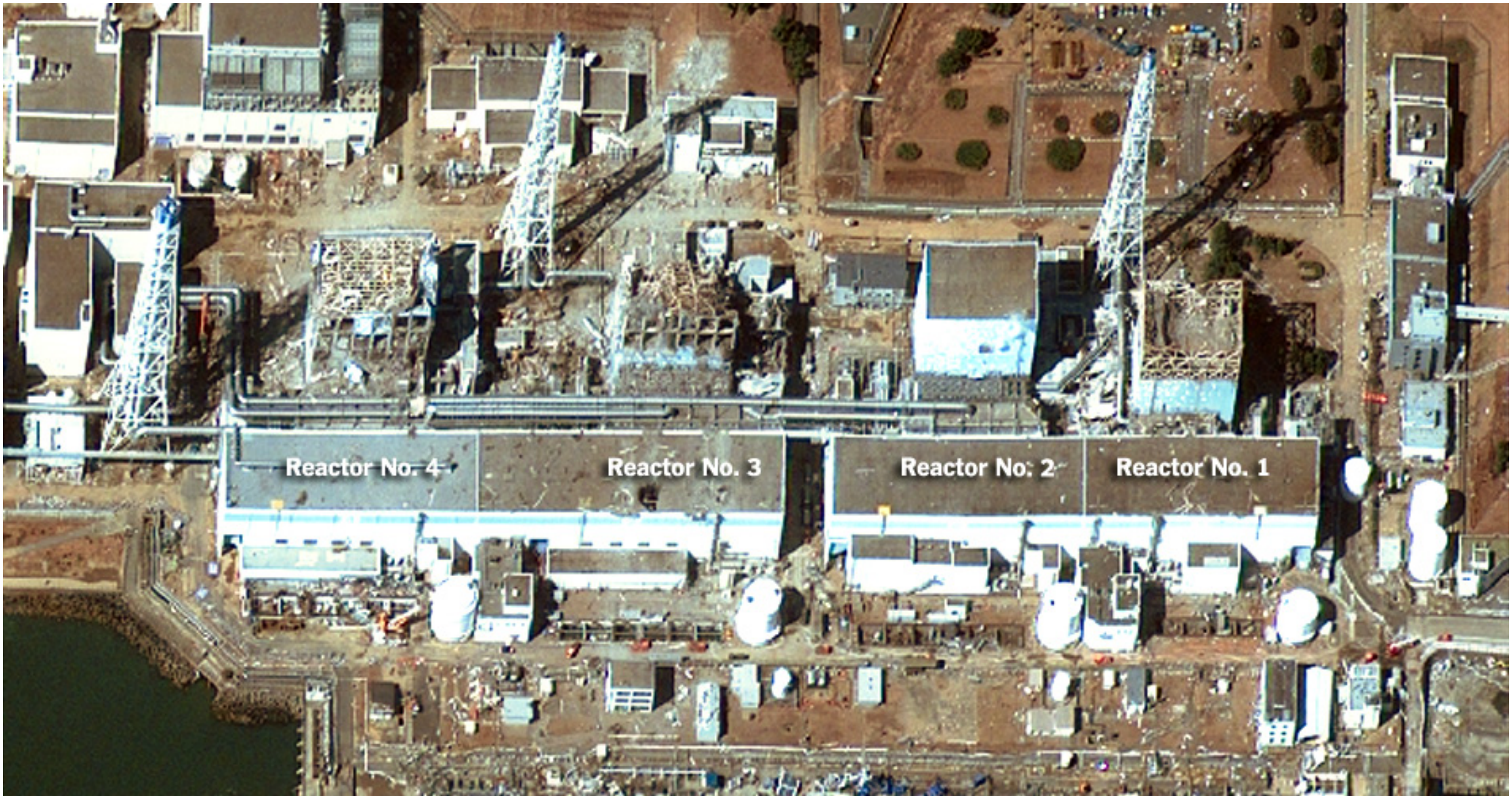
プールについての重要な疑問

- プールや燃料棒は損傷しているか?
  - 地震
  - 水素爆発
  - クレーンや構造物の破片がプールへ落下? 第３原子炉での可能性
  - ４つの全ての建屋で、使用済燃料棒プールの格納物および冷却機能が無い可能性.
- 現在の状況?
  - 冷却水の量, 温度?
- 崩壊熱除去機能が働いているか?
  - 働いていなければ, プールに水を投入し続ける必要がある
    - 水はどこに行くのか? 蒸発 vs 建屋への漏出

Thursday, March 17, 2011				
	6:15:00	17.26	135.45	Unit 3 - Pressure of suppression pool increased, considered venting.
	9:48:00	17.41	139.00	Helicopters drop water on Unit 3 roof until 10:01.
	11:30:00	17.48	140.70	Workers return, restart water injection in Unit 3.
	19:05:00	17.80	148.28	Water spray on Unit 3 from high pressure trucks from ground until 20:09
Friday, March 18, 2011				
	14:00:00	18.58	167.20	Water spray onto unit 3 by 6 fire engines of SDF until 14:38
	14:45:00	18.61	167.95	Water spray onto unit 3 by US Military fire engine
Saturday, March 19, 2011				
	0:30:00	19.02	177.70	Water spray onto unit 3 by Tokyo Fire Dept until 1:10
	14:10:00	19.59	191.37	Water spray onto unit 3 by Tokyo Fire Dept until 3:40 on 20 March.
Sunday, March 20, 2011				
	11:00:00	20.46	212.20	Unit 3 PCV pressure rose to 320 kPa then fell.
	15:05:00	20.63	216.28	Seawater injection into Unit 2 SFP via cooling line. Continues until 17:20 40 tonne water injected.
	15:46:00	20.66	216.97	Power center electricity restored on Unit 2.
	18:30:00	20.77	219.70	Unit 4 SFP water spray until 19:46 by SDF.
	21:36:00	20.90	222.80	Water spray onto unit 3 by Tokyo Fire Dept until 3:58 on 21 March.

Monday, March 21, 2011				
	6:37:00	21.28	231.82	Unit 4 SPF water spray by SDF until 8:41
	8:58:00	21.37	234.17	Radiation dose at site boundary around main entrance exceeds limit value. Only large fluctuations beyond 0.5 mSv/hr will be reported as new events from now on.
	10:37:00	21.44	235.82	Water spraying on common spent fuel pool started, ended at 3:30 pm
	15:37:00	21.65	240.82	Electricity connected to common spent fuel pool
	15:55:00	21.66	241.12	Grayish smoke from Unit 3 refueling area continuing until 17:55
		21.75	243.20	1.75 mSv/hr spike at front gate MP
	18:22:00	21.77	243.57	Light gray smoke from Unit 2 refueling floor area. Continued to 07:11 22 March, decreasing amount, white color.
Tuesday, March 22, 2011				
	10:35:00	22.44	259.78	Unit 4 power center electricity on.
	15:10:00	22.63	264.37	water spray on Unit 3 from Tokyo and Osaka Fire Dept until 16:00
	16:07:00	22.67	265.32	Injection of 18 tonne seawater to Unit 2 SFP
	17:17:00	22.72	266.48	Water injection by concrete pumping truck into Unit 4 fuel pool, 50 t/hr until 20:30
	22:46:00	22.95	271.97	Lights turned on in Unit 3 control room
Wednesday, March 23, 2011				
	2:33:00	23.11	275.75	Seawater injection into Unit 1 RPV through feed water system in addition to fire lines. Flow rate increased to 18 m3/h
	9:00:00	23.38	282.20	Unit 1 Switched to feed water system only. Flow rate is 11 m3/h
	10:00:00	23.42	283.20	Core temperature 400C in Unit 1
	10:00:00	23.42	283.20	Pumping water into Unit 4 fuel pool until 13:02
	11:03:00	23.46	284.25	Pumping 35 tonne of seawater into Unit 3 fuel pool until 13:20
	16:20:00	23.68	289.53	Black smoke belching from Unit 3 building. Not observed at 11:30 pm or 04:50 next day.
Thursday, March 24, 2011				
	5:35:00	24.23	302.78	Injecting 120 tonne seawater into Unit 3 SFP until 16:05
	10:50:00	24.45	308.03	White fog-like steam from roof of Unit 1 reactor bldg.
	11:30:00	24.48	308.70	Lights on in main control room, Unit 1.
	13:28:00	24.56	310.67	Unit 3 water spray on SFP until 16:00
	18:02:00	24.75	315.23	Unit 3 fresh water injection to core started

3/18



NY Times – DigitalGlobe

ヘリコプターによる水の投下

17 March NHK/Getty/AFP

3月18日　第4号機

自衛隊

3月22日

東京電力

使用済み燃料の冷却　第4号機

東京電力　2011年3月22日撮影

2011年3月25日(金)				
	6:05:00	25.25	327.28	第4号機使用済み燃料置場への，冷却管からの海水注入(10時20分まで)
	10:30:00	25.44	331.70	第2号機使用済み燃料置場への，海水注入(12時19分まで)
	13:28:00	25.56	334.67	第3号機上への水の噴霧(16時00分まで)
	15:37:00	25.65	336.82	第1号機原子炉圧力容器への真水の注入開始
	18:02:00	25.75	339.23	第3号機原子炉圧力容器への真水の注入開始
	19:05:00	25.80	340.28	コンクリートポンプ車による，第4号機使用済み燃料置場への水の注入(22時07分まで)
2011年3月26日(土)				
	10:10:00	26.42	355.37	第2号機へ真水とホウ酸の注入開始
	16:46:00	26.70	361.97	第2号機 主管制室のライトをつける
2011年3月27日(日)				
	12:34:00	27.52	381.77	コンクリートポンプ車による第3号機上への水の噴霧
	15:30:00	27.65	384.70	第1，2号機の外溝の水質検査　第1号機0.4 mSv/h，第2号機 >1000 mSv/hr in unit 2.
	16:55:00	27.70	386.12	コンクリートポンプ車による第4号機上への水の噴霧
2011年3月28日(月)				
	12:00:00	28.50	405.20	第1，2，3号機のタービン建屋の基礎部の水に高レベル放射能が観測される.
	17:40:00	28.74	410.87	第3号機の復水貯蔵タンクから第1号機の圧力抑制プール のサージタンクへ水を移動(3月31日08時40分まで).
	20:30:00	28.85	413.70	第3号機の炉心に電動機駆動ポンプを使って水を注入
2011年3月29日(火)				
	8:32:00	29.36	425.73	一時的に電動機駆動ポンプを用い，第1号機の炉心への水注入へ切り替える.
	11:50:00	29.49	429.03	第4号機 主管制室のライトをつける
	14:17:00	29.60	431.48	コンクリートポンプ車による第3号機使用済み燃料置場への水の噴霧(18時18分まで)
	16:45:00	29.70	433.95	第2号機の復水貯蔵タンクから第1号機の圧力抑制プール のサージタンクへ水を移動 (4月1日01時51分まで)

損傷した発電所のビデオ映像と写真

発電所のビデオ撮影(東電ヘリ) 3月17日 3:07pm
http://www.youtube.com/watch?v=oQ4TqMZq-rs&feature=player_detailpage

消防による第3号機への放水 3月19日 4:58pm
http://www.youtube.com/watch?v=v8Tds5d-ApU&feature=player_detailpage

第4号機への放水 地上からの映像 3月22日 0:56am
http://www.youtube.com/watch?v=Hs2AUmmUcKQ&feature=player_detailpage

自衛隊ヘリからの映像 3月23日 5:00
http://www.youtube.com/watch?v=mI2vYcxc16A&feature=player_detailpage

自衛隊ヘリからの映像について，NHKによるコメント 3月27日
http://www.youtube.com/watch?v=wAEixbcPhG4&feature=player_detailpage

航空写真 (高画質)
http://cryptome.org/eyeball/daiichi-npp/daiichi-photos.htm

制御室　3月23日

東電

暗所での作業

東電 3月23日

計器を読む職員

Tepco March 23

第2号機の制御室　3月26日

東電

最新情報はこちらから

- http://www.nisa.meti.go.jp/
- http://www.tepco.co.jp/index-j.html
- http://www.iaea.org/

現状(4月6日時点)

福島第一原子力発電所の状況は極めて深刻である。-
IAEA April 6

This will not lead to a sustainable condition. We want to restore power and rebuild the cooling system, but such efforts are hampered by the stagnant water,We have to find a way out of the contradictory missions” of the incoming water and the removal of contaminated water

（これは，継続的に続くということではない．電源を回復し冷却システムを再構築したいが，注水がうまくいかず努力が報われていない．注水と汚染水の除去という悩ましい問題をなんとか打開する方法を見つけなければならない．）

共同通信社による，原子力安全・保安院，西山英彦氏の記者会見の様子．3月30日

各発電所の現状(4月6日時点)

IAEA による情報　http://www.jaif.or.jp/english/
さらなる情報はこちらから　http://www.nisa.meti.go.jp/english/

Unit	1	2	3	4
Core and fuel integrity	Damaged	Severe damage	Damaged	No fuel in the Reactor
RPV & RCS integrity	RPV temperature high but stable	RPV temperature stable	RPV temperature stable	Not applicable due to outage plant status
Containment integrity	No information	Damage suspected	Damage suspected	
AC Power	AC power available - power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room	AC power available – power to instrumentation – Lighting to Central Control Room
Building	Severe damage	Slight damage	Severe damage	Severe damage
Water level of RPV	Around half of Fuel is shown uncovered (Stable)	Around half of Fuel is uncovered (Stable)	Around half of Fuel is uncovered (Stable)	Not applicable due to outage plant status
Pressure of RPV	Increasing	Stable	Stable	
CV Pressure Drywell	Decreasing trend	Stable	Stable	
Water injection to RPV	Injection of freshwater – via mobile electric pump with off-site power	Injection of freshwater – via mobile electric pump with off-site power	Injection of freshwater – via mobile electric pump with off-site power	
Water injection to CV	No information	No information	No information	
Spent Fuel Pool Status	Fresh water spraying completed by concrete pump truck	Freshwater injection to the Fuel Pool Cooling Line	Freshwater injection via Fuel Pool Cooling Line and Periodic spraying	Fresh water spraying completed by concrete pump truck

冷却水について　2011年4月4日

- **冷却は水の損失総量に左右される**
  - 原子炉残留熱除去系が機能していない.
  - 冷却水のポンプ注入，加熱，煮沸され水蒸気として放出
  - 水蒸気は蒸気柱となって大気へ流出，または内部構造中にて凝結し，地下/汚水槽/復水タンクへ流出.
- **冷却水の流速は現状，かなり制限されている.**
  - 2 ～ 15トン/時
  - 効果的な除熱のためには，より大きな流速が必要である.
- **配管系統/格納容器/建屋への損傷は，高濃度汚染水が直接海へ流れ出すなどの環境への漏出につながる**
  - 貯蔵水の不足 (1000トン/日が必要)
  - スペース確保のための汚染水の投棄
- **水の注入を停止すると炉心が溶融し，原子炉圧力容器(RPV)と格納容器の破損が起こり, 多量の核分裂生成物(FP)が大気中へ放出される可能性がある.**

“矛盾のある，悩ましい問題”

全般的な見解　4月6日

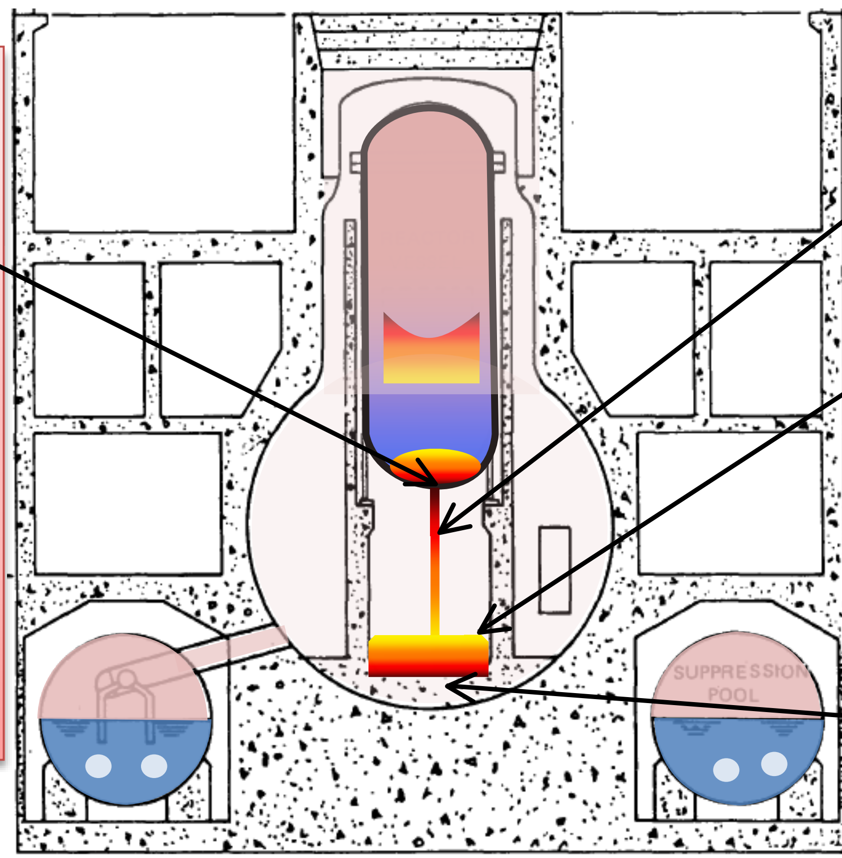
- 第1～4号機の廃炉 (東電)
- 原子炉/タービンの建屋内および周辺部は高度に汚染されている.
- 極めて危険な環境(高放射線,破片), 評価することさえ困難であり, ましてや修繕はもっと困難
- 遠隔電源は復旧したが, どの程度の数の装置が動作可能となったかは不明確である.
- おぼつかない 運用状況 - 安全システムの欠如,格納容器の欠損, その場しのぎの冷却測定, 非常に損傷しやすい状況.
- かなりの努力が必要である
  - 冷却維持
  - 核分裂生成物の放出の囲い込み
  - 周辺エリアの汚染除去
- 長期にわたる廃炉への努力 (スリーマイル, チェルノブイリの例から考えて10年スパン)

炉心の位置は？　メルトダウンしているのか？

Damaged core material may slump to lower head.

Now becomes much more difficult to cool.

If temperature is sufficiently high, melting may take place.



If core is molten, it can dissolve RPV steel and penetrate lower head.

A portion of the molten core could then fall to bottom of the reactor cavity.

If that happens, core will wind up eating into concrete "basemat" and possibly through primary containment

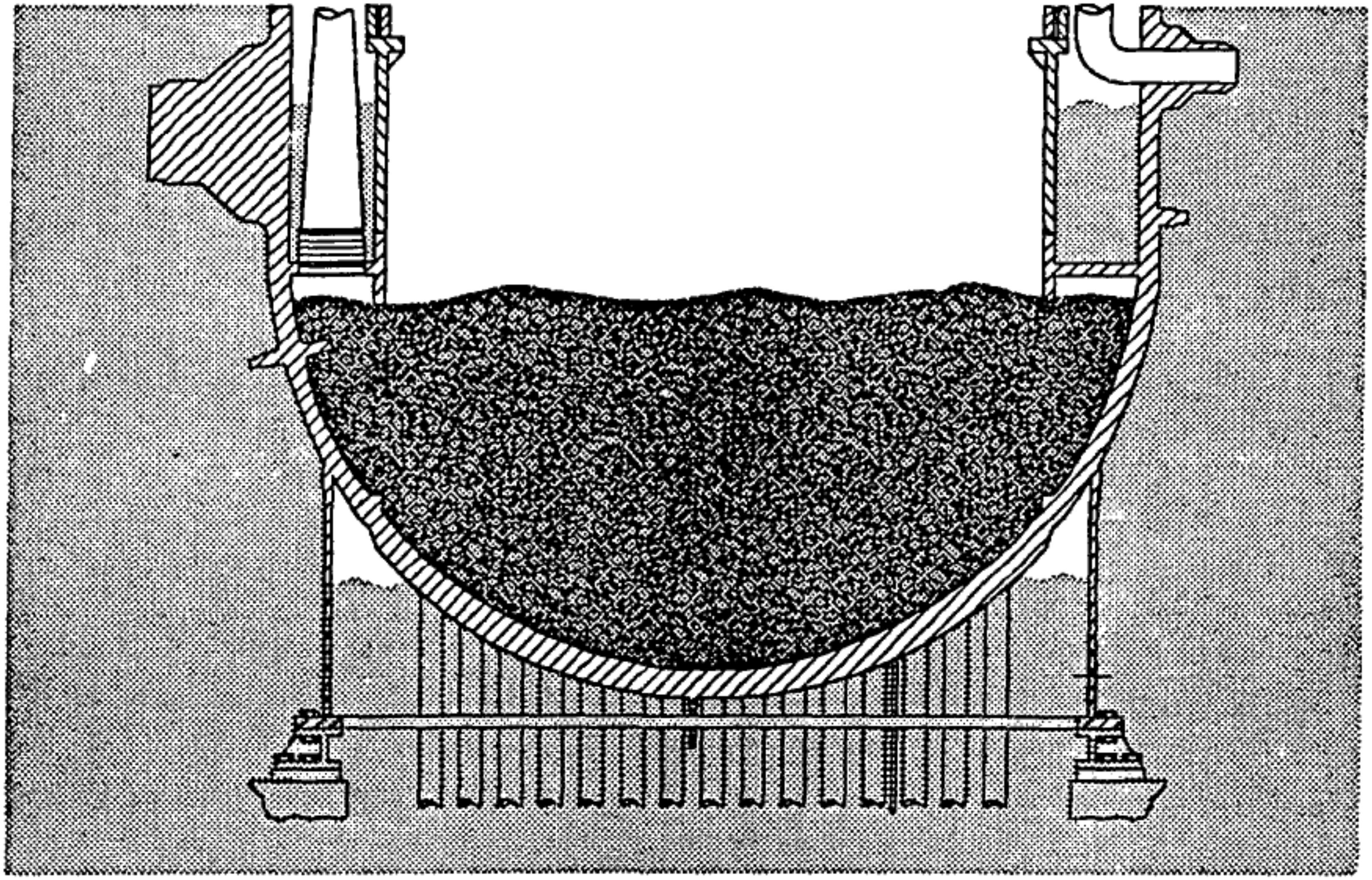
炉心が溶融し、圧力容器を貫通する可能性はあるのか？

炉心の温度と位置による。スリーマイルの時は、切迫していた。

- 現状
  - Cores are severely damaged
  - Some core material may have moved to lower head
  - Difficulty getting sufficient water into reactor to keep reactor vessel and core cool
- 緊急処置の対応策
  1. Keep vessel depressurized
  2. Vent to keep containment depressurized
  3. Restore injection in a controlled manner
  4. Inject boron
  5. Flood containment to delay/prevent lower head failure

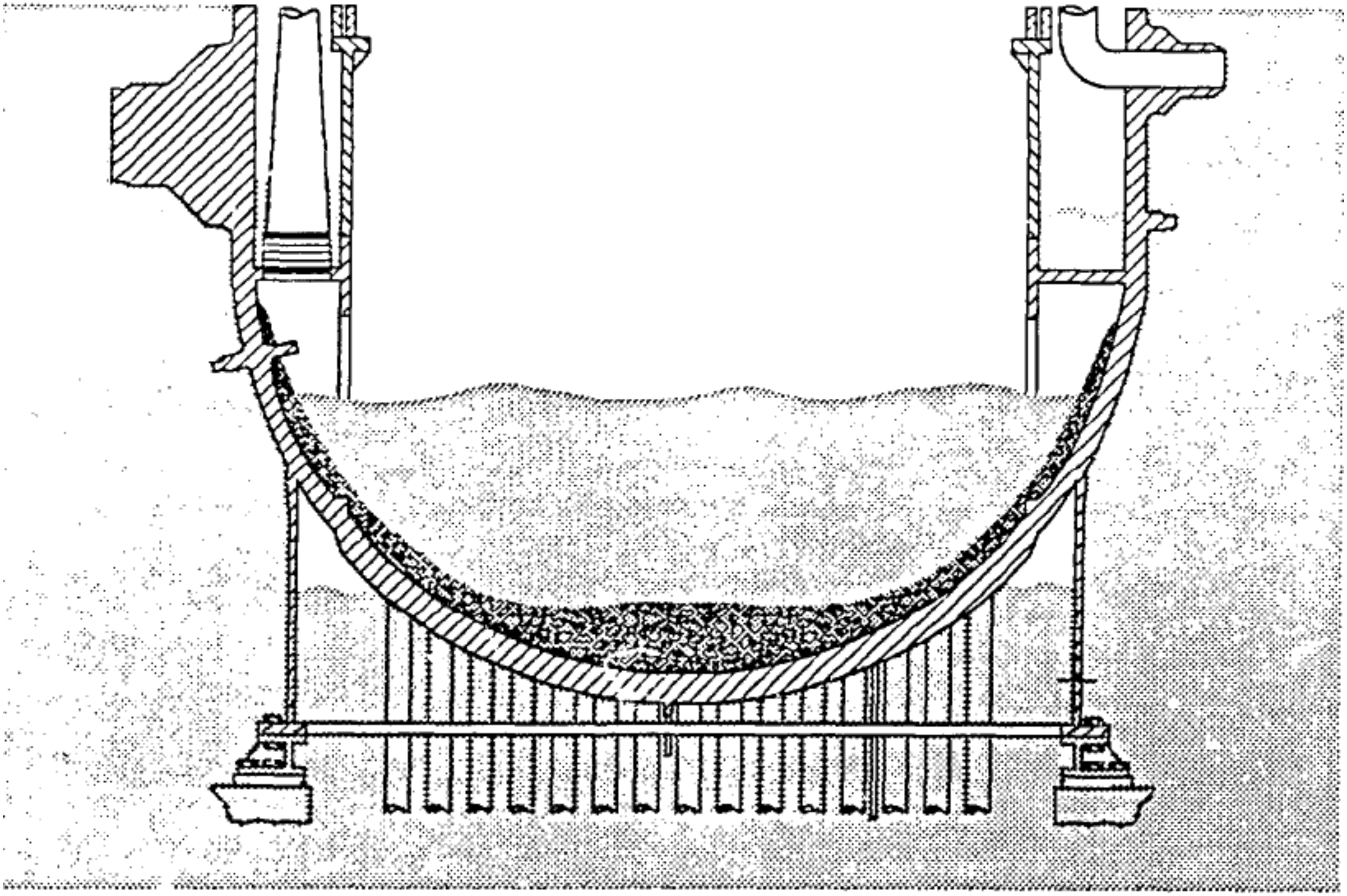
NUREG/CR-5869 Hodge et al CONF-921007—31 ORNL

圧力容器底部に溜まった燃料デブリ



Hodge et al CONF-921007—31 ORNL

コリウム(炉心溶融物)の生成



Hodge et al CONF-921007—31 ORNL

それぞれの対策と起こりうる現象

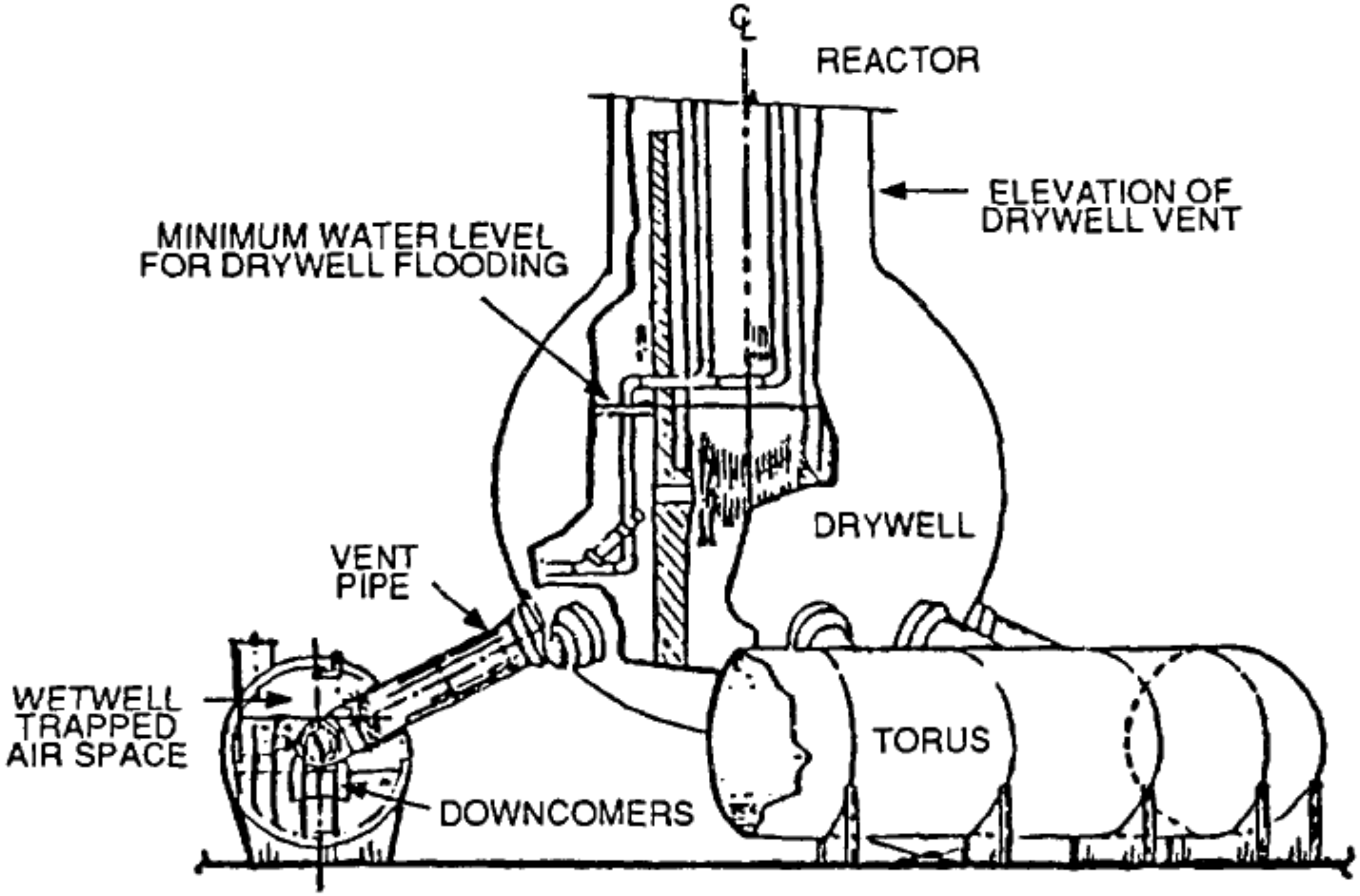
Drywell Flooded?	Skirt Vented ?	Failure Mechanism	Time to Failure (hr)
N	N	Penetrations	4.
N	N	Bottom head creep rupture	10
Y	N	Bottom head creep rupture	13
Y	Y	Melting upper vessel wall	>20

Drywell can only be flooded up to vents. "The mass of the BWR internal structures is large…nevertheless, decay heating of the debris pool and the associated upward radiation would be relentless and, after exhaustion of the stainless steel, the only remaining internal heat sink above the pool surface would be the carbon steel of the vessel wall."

Hodge et al. CONF-921007—31 ORNL

圧力容器底部の破損を防ぐ方策

圧力容器底部が浸かるように格納容器を水で満たす



Hodge et al CONF-921007—31 ORNL

ベント作業

- Used to reduce primary containment pressure to avoid failure and associate release
- Design pressure 400 kPa
- Failure pressure (estimated) 1000 kPa
- Vent through filters to stack
- Careful! High pressures will failure duct work and contaminate reactor building.
- Primary initially inert, environment will be steam/N2/H2 after severe accident

- Venting paths
  - 18-inch torus vent path,
  - 18-inch torus supply path,
  - 2-inch drywell vent to SBGT,
  - Two 3-inch drywell sump drain lines,
  - 6-inch ILRT line from drywell (does not fail ducts)
  - 18-inch drywell vent path, and (fails ducts)
  - 18-inch drywell supply path. (fails ducts)

NUREG 1150

ベントのしくみ

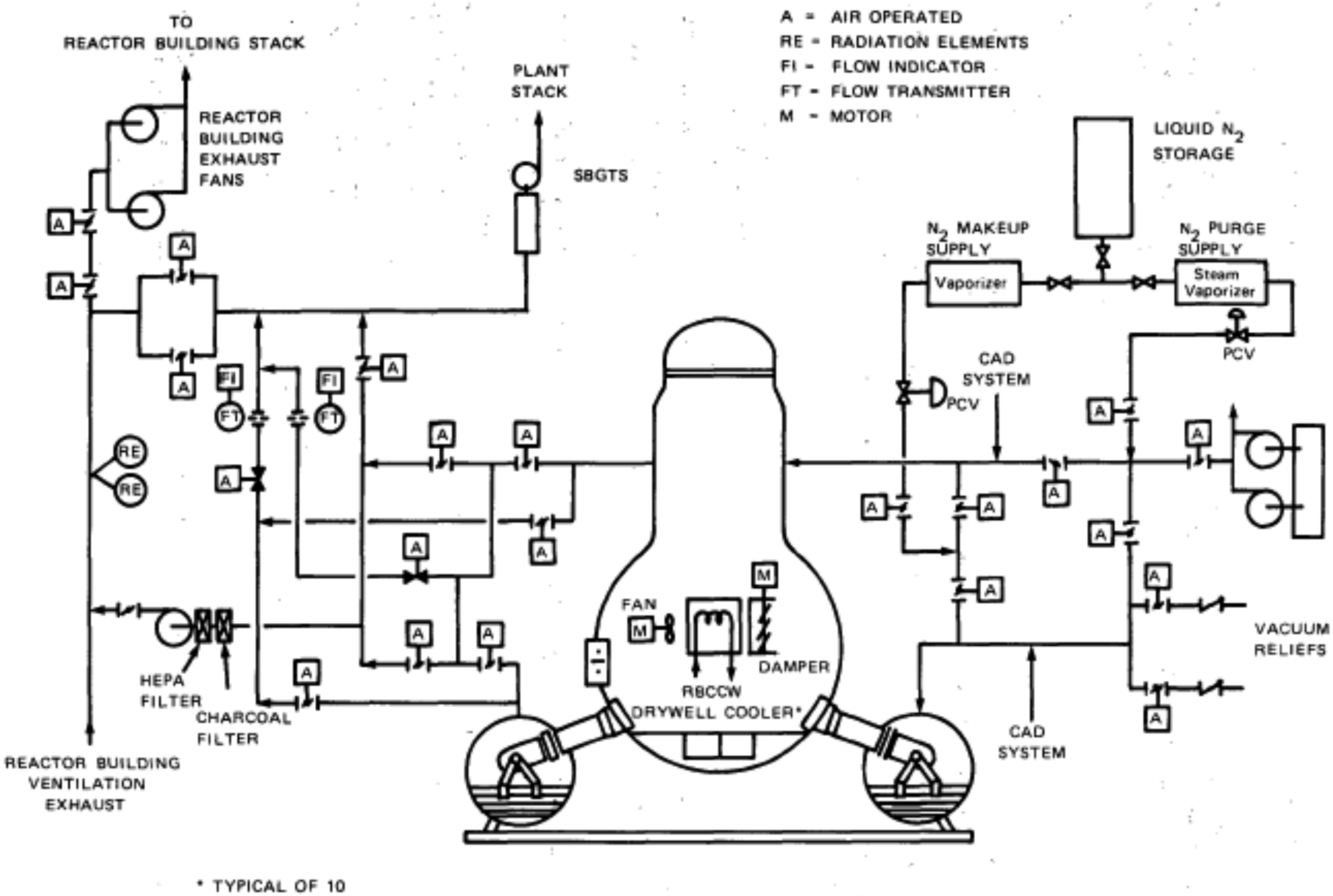


Fig 4-31 NUREG/CR-2726 LWR H2 Manual 1983

緊急時のベント対応策

- なぜベントするか？
  - 水素の蓄積を最小限に
  - 一次格納容器を保つため
- 沸騰水型原子炉（BWRs）は重大事故時ベントすることが承認される
  - Suppression pool expected to “scrub out” some fission products – but bypasses standard air filtration
  - Success depends on accident progression, venting timing
  - Need to chose vent path carefully, make sure valves close (!) after completion
  - Need to protect operators from release
- 長期的な崩壊熱除去方法がなくなるリスクを下げうる

Dallman et al Nuclear Engineering and Design 121, 421-429, 1990.

ベント実施の結果

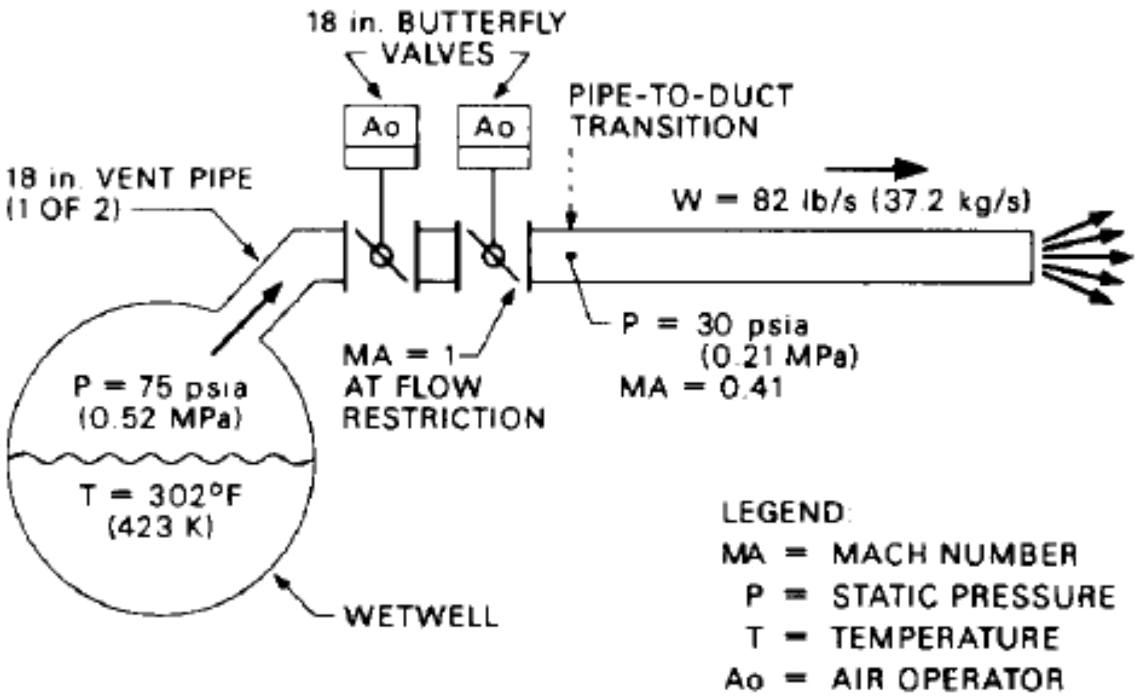


Fig. 3. Venting at elevated pressure would fail ventilation system ductwork in the torus room.

Harrington et al 1988, Kelly 1991,
US NRC Generic Letter 89-16, Sept 1989.

Flashing of suppression pool water leading to Loss of "net positive suction head" and failure of RCIC pump

Filling reactor building with hot steam, H2 and possibly, fission products.

US NRC recommended all US Mark I BWRs install a hard vent line to avoid venting directly into the reactor buildings

起こりえる封じ込め失敗の可能性

NUREG 1150 4.3.1 The estimated mean failure pressure for Peach Bottom's containment system is 148 psig, which is very similar to that for large PWR containment designs. However, its small free volume relative to other containment types significantly limits its capacity to accommodate noncondensible gases generated in severe accident scenarios in addition to increasing its potential to come into contact with molten core material. The complexity of the events occurring in severe accidents has made predictions of when and where Peach Bottom's containment would fail heavily reliant on the use of **expert judgment** to interpret and supplement the limited data available.

4.4.2 An important consideration in determining the magnitude of building decontamination is whether hydrogen combustion occurs in the building and whether combustion is sufficiently energetic to fail the building.

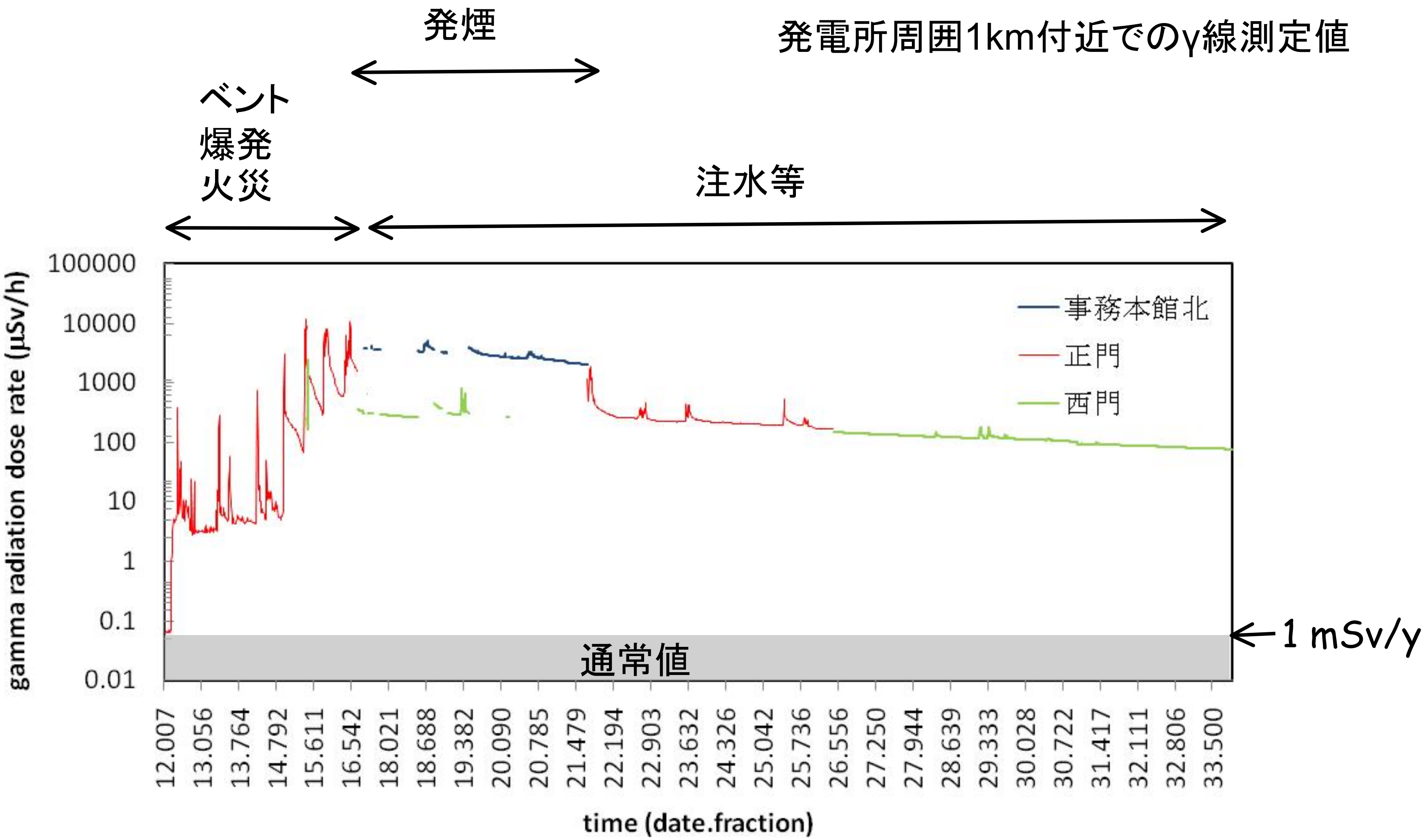
予想される結果

1. 冷却機能が回復した場合- core damaged but does not fail RPV. Plant contaminated, has to be cleaned up enough to repair key systems, allow human entry and dispose by dismantling (TMI). If too damaged or contaminated, requires entombment in place (Chernobyl).
2. 冷却されない場合- molten material melts through RPV and drops to bottom of primary containment vessel, failure of containment, possible steam explosion, generation of gases due to core-concrete interactions. Requires entombment and long term custody of unconfined core.

外部への放射能の影響

-汚染の広がりと市民の被ばくの可能性-

核分裂生成物の大気中への放出

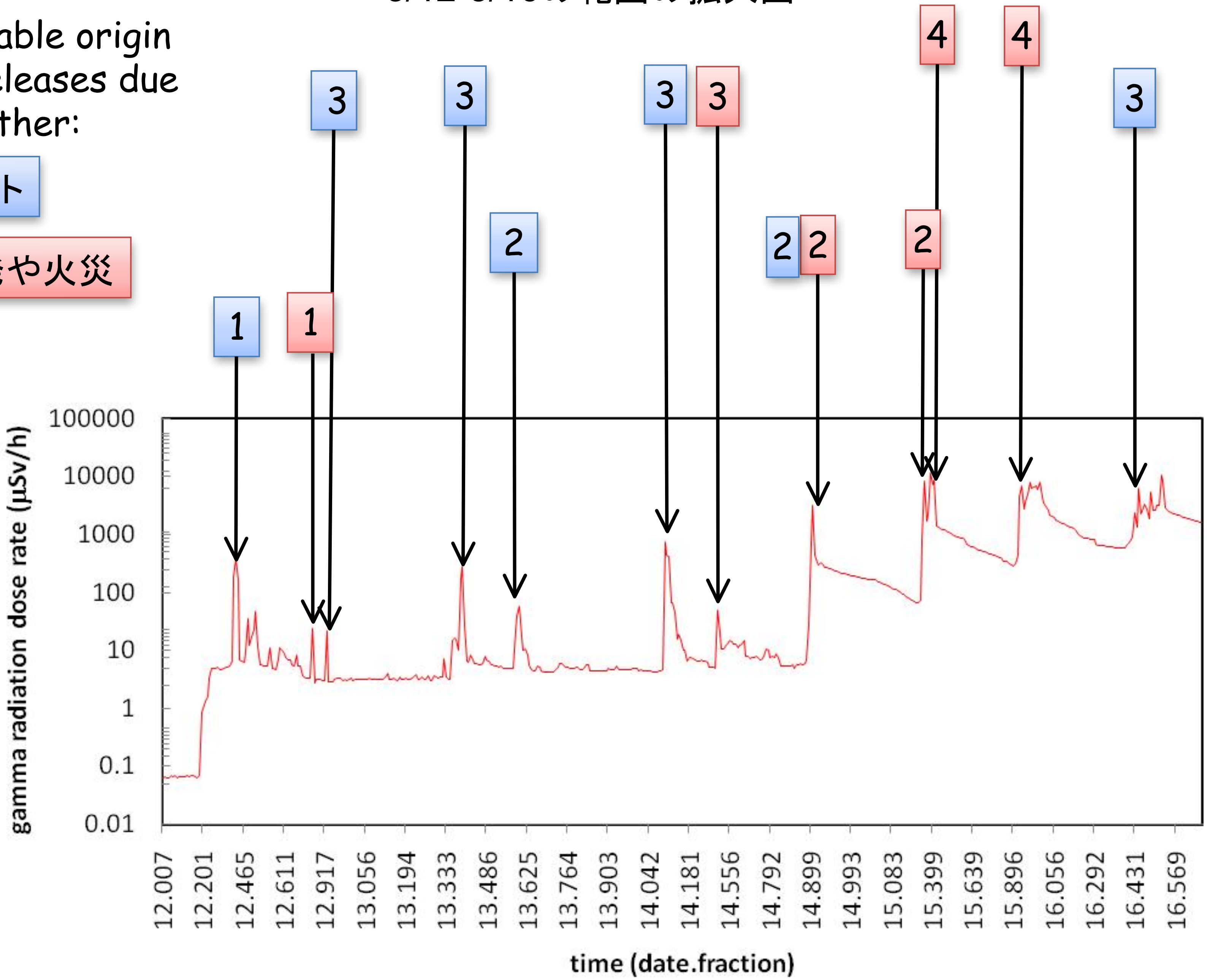


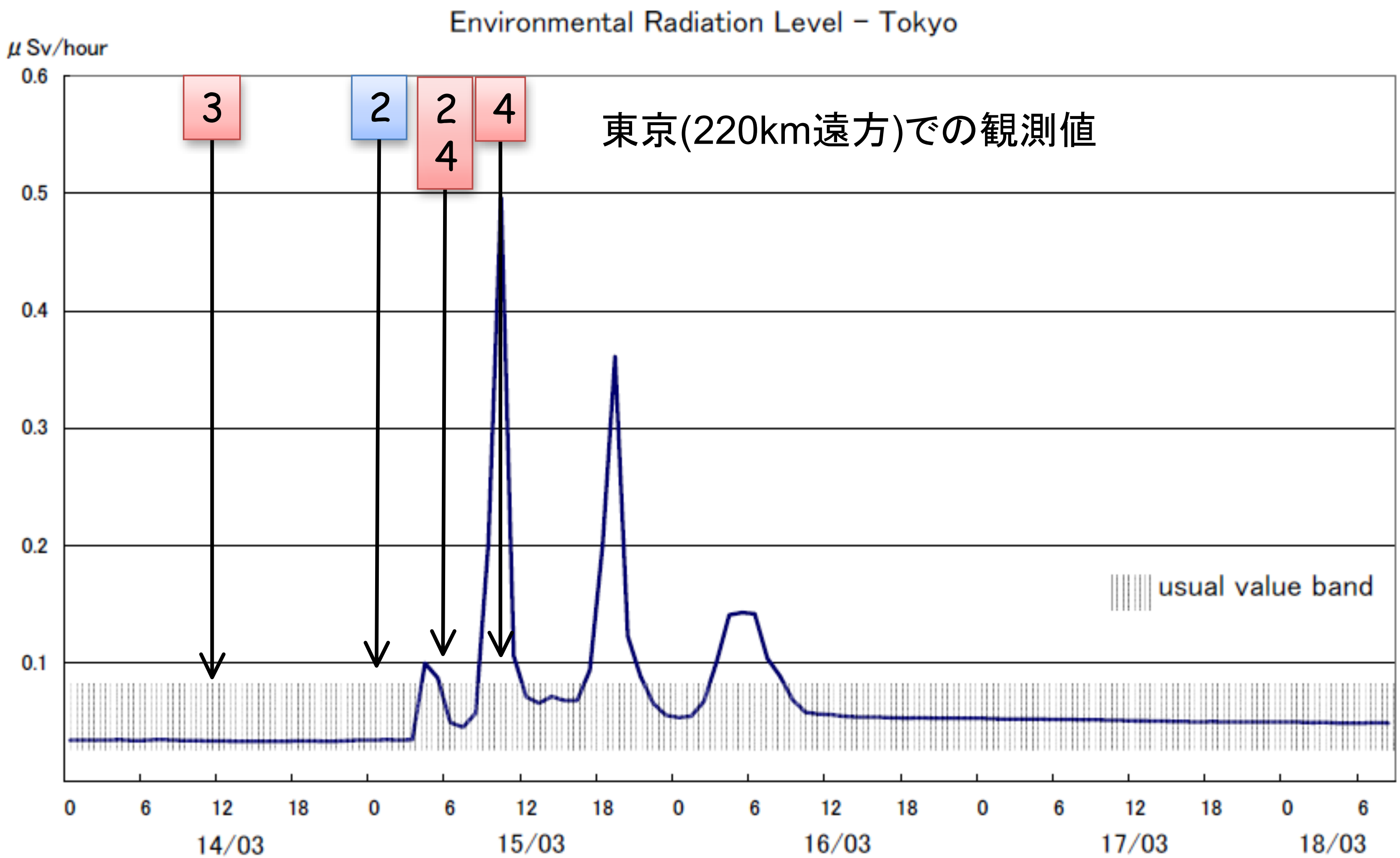
3/12-3/16の範囲の拡大図

Probable origin of releases due to either:

ベント

爆発や火災





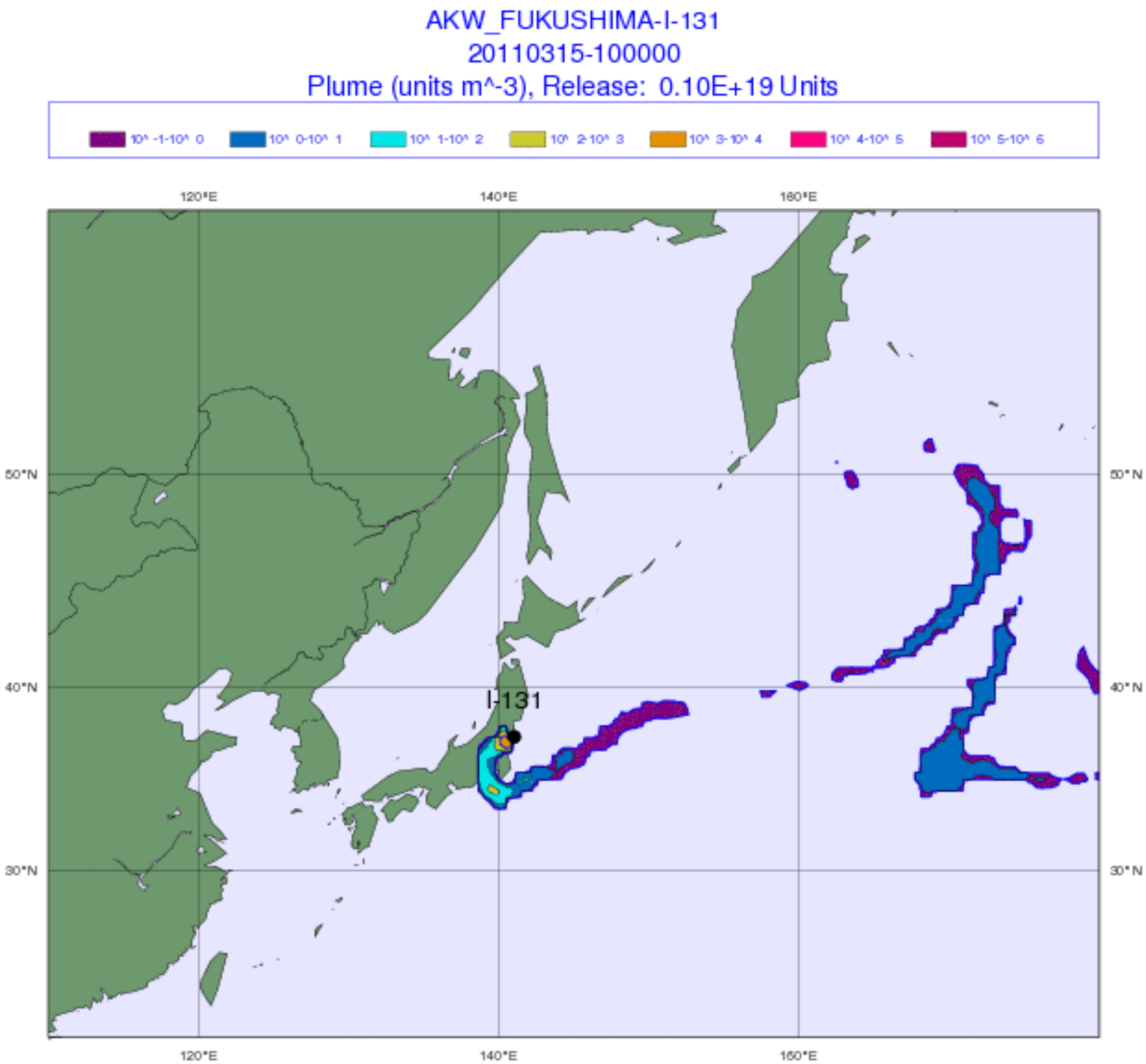
http://www.mext.go.jp/component/a_menu/other/detail/__icsFiles/afieldfile/2011/03/19/1303902_1818_5_2.pdf

訳注:リンク切れ

主に懸念される核分裂生成物

- 気体
  - クリプトン(Kr)-85
  - キセノン(Xe)-133
- 揮発しやすい固体
  - ヨウ素(I)-131, 132　融点=113度
  - セシウム(Cs)-134, 136, 137 融点=28.5度
  - テルル(Te)-127, 129, 132 融点=450度
- 放射線の危険: β 線と γ 線
  - $^{137}Cs \rightarrow {}^{137}Ba + \gamma + e^-$　(0.97 MeV)　$t_{1/2}$ = 30 y
    長期的な懸念　大気中を広がって地面に落ち、植物などに影響
  - $^{131}I^- \rightarrow {}^{131}Xe + \gamma + e^-$　(1.17 MeV)　$t_{1/2}$ = 8 d
    短期的な懸念　甲状腺に取り込まれる

ヨウ素-131の拡散予測の一例



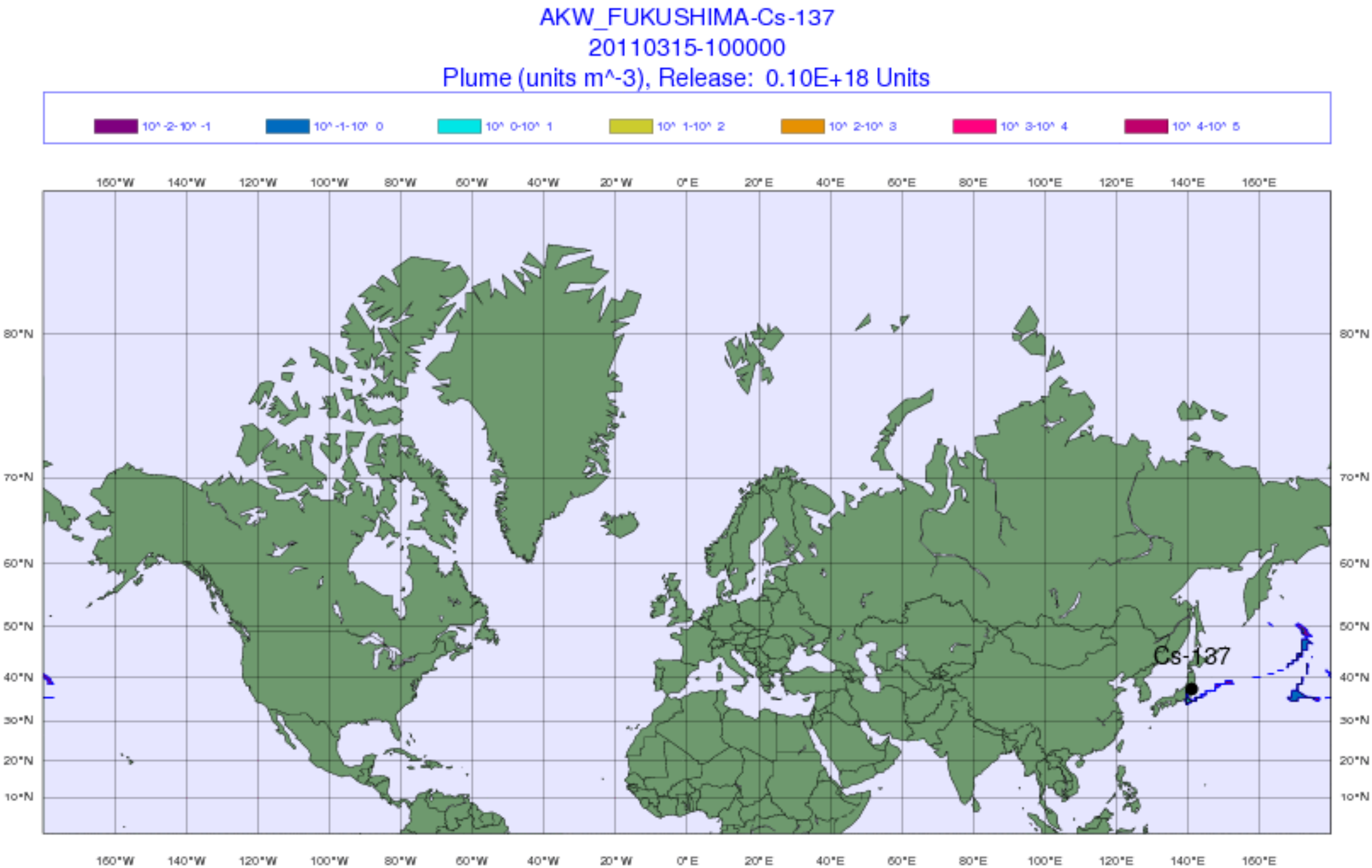
http://www.zamg.ac.at/

Continuous source term.

Global circulation model

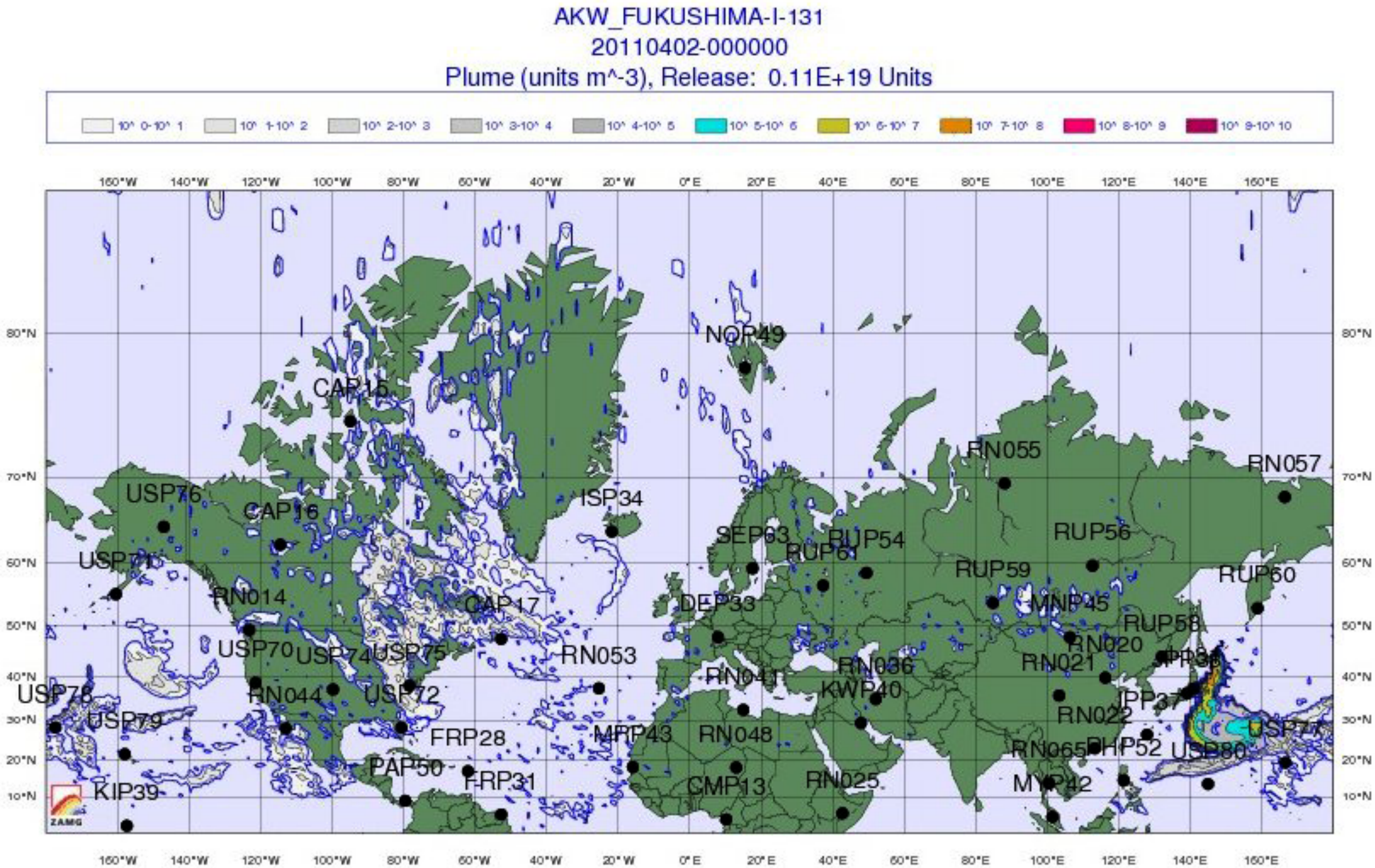
Bounding assumptions about chemistry

セシウム-137の拡散予測の一例



http://www.zamg.ac.at/

世界の核実験監視基地

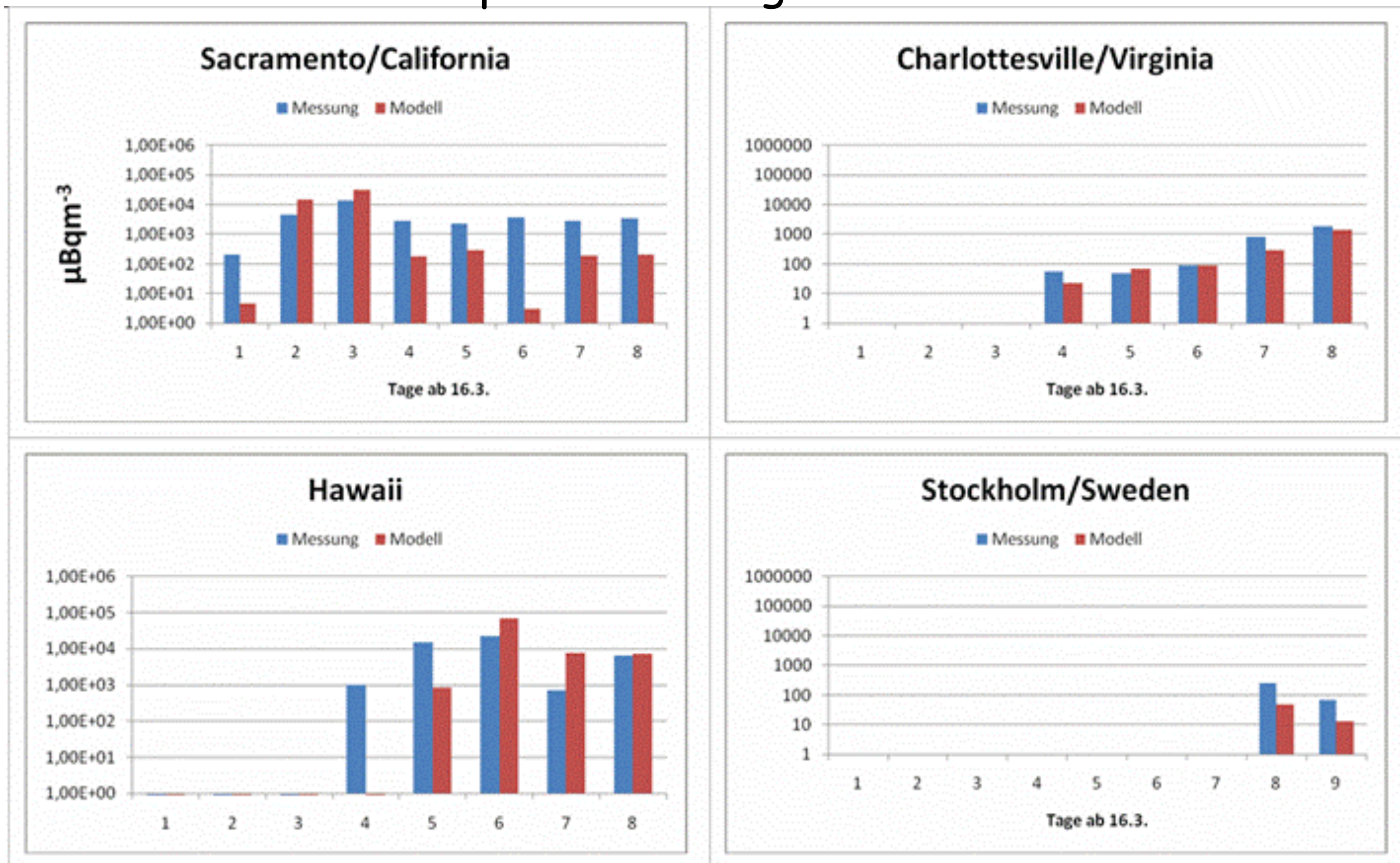


http://www.zamg.ac.at/

世界で観測されたI-131

Model results based on a release of 10^{17} Bq per day at Fukushima since 12. March 2011 08:30 UTC. In the model, dry deposition (contact with the ground) and wet deposition (to wash out the particles) are fully considered. The input comes from the European center for medium-term weather forecast. The dispersion model is FLEXPART version 8. http://www.zamg.ac.at/

EPA 22 March analysis of SF air samples	
	μBq/m³
Cs-137	48
Te-132	277
I-132	244
I-131	2516



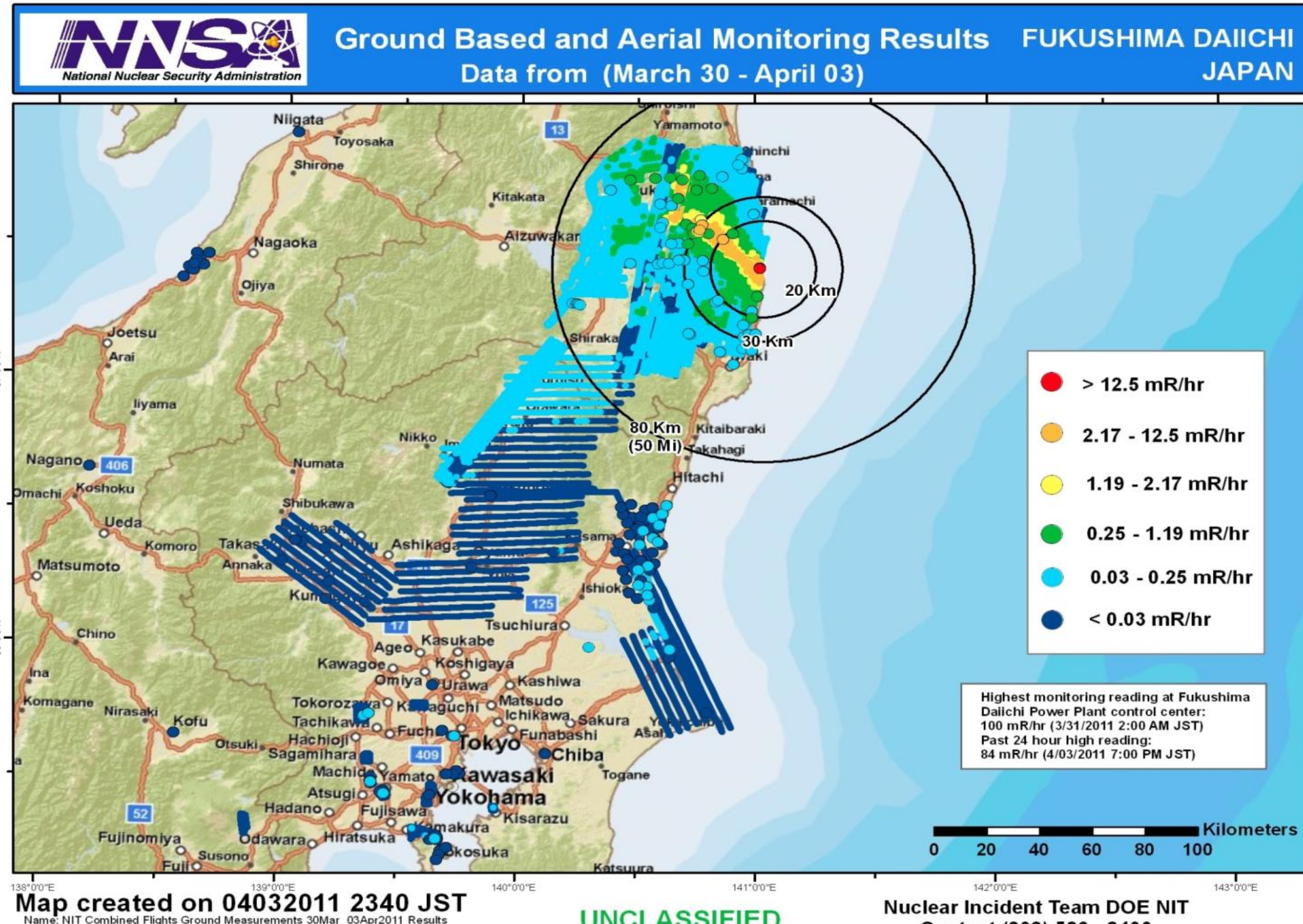
放出された放射性物質の量を予測する（計算例）

- ZAMG (Austria) numerical simulations
  - Weather forecast from the ECMWF global circulation model
    - 25 km horizontal, 91 vertical levels, 12 min time step
  - Lagrangian particle dispersion model FLEXPART V. 8
  - Adjusted source term to match selected CTBT station data
- Results as of 1 April 2011. Release in Bq

核種	福島第一	チェルノブイリ	地上核実験
I-131	10^{16} to 7×10^{17}	1.8×10^{18}	9×10^{20}
Cs-134	?	5.0×10^{16}	-
Cs-137	10^{15} to 7×10^{16}	8.5×10^{16}	1.3×10^{18}
計	> 7.7×10^{17}	9.4×10^{18}	
	ZAMG 30 March 2011	UNSCEAR 2000	UNSCEAR 1982

（訳注：拡散シミュレーションを考慮した上で、世界各地で観測された放射性物質の量を説明できるように、放出量の見積もりを行っている。不確定要素が多く、現段階での正確な推定は困難。なお、4/12公開の保安院、安全委による推計も桁として同程度。）

アメリカNNSAによる放射線レベルの測定

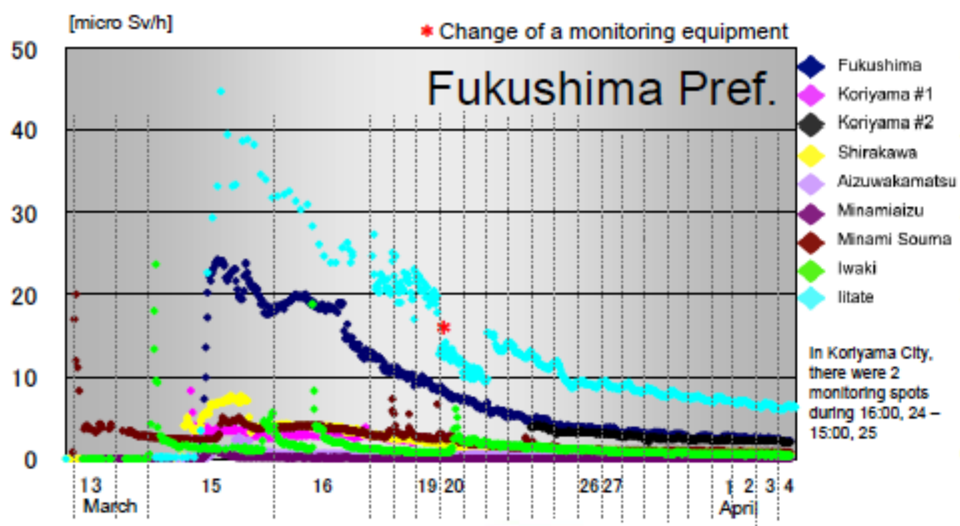


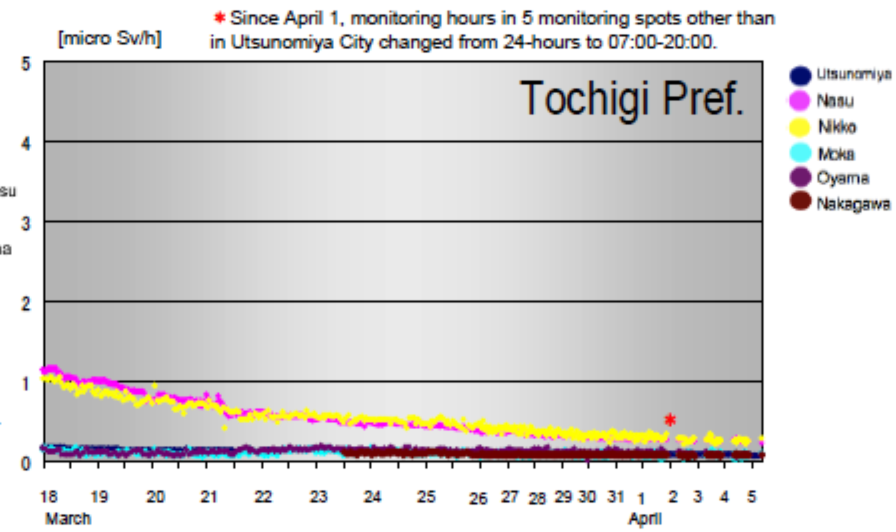
NNSAによる測定結果のまとめ (4/3時点)

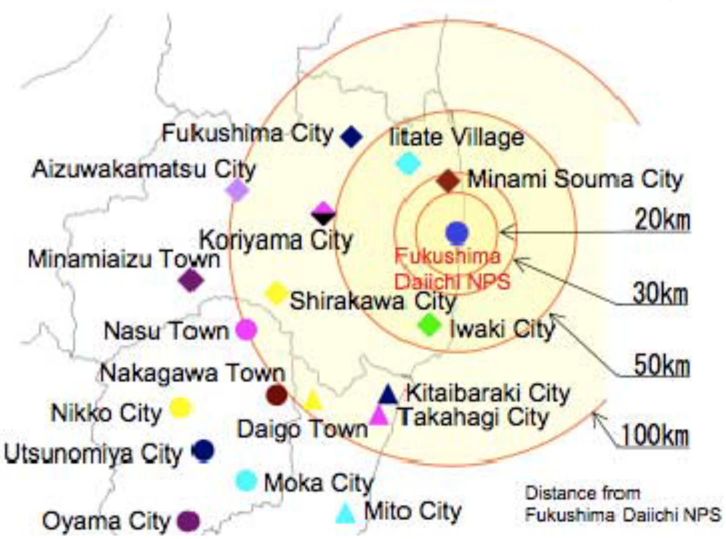
- 高さ1mでの値(1 mR/h = 10 μSv/h)
- すべて30 mR/h(300 μSv/h)以下
  - 有意だが低い値。
  - バックグラウンドは 0.1 ~1 μSv/h
    - (0.7 μSv/h = 6.2 mSv/yr が平均)
- 40kmの外側では、避難や移住が必要とされるレベルを一貫して下回っている。
- 3/19以降、放射性物質の大きな降下は無い。

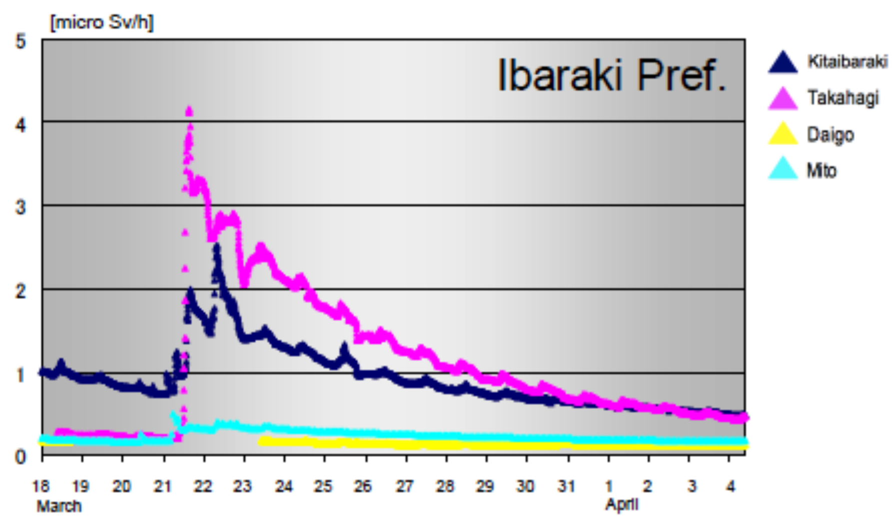
http://blog.energy.gov/content/situation-japan/

日本の文科省と保安院による測定









http://www.jaif.or.jp/english/

訳注：最新のデータはこちらから（日本語）
http://www.mext.go.jp/a_menu/saigaijohou/index.htm

IAEAアセスメント(3/28時点）

On 28 March, deposition of iodine-131 was detected in 12 prefectures, and deposition of cesium-137 in 9 prefectures.

Prefecture of Fukushima

23000 Bq/m^2 for iodine-131
90 Bq/m^2 for caesium-137.

Other prefectures

1.8 to 280 Bq/m^2 for iodine-131
5.5 to 52 Bq/m^2 for caesium-137

In the Shinjyuku district of Tokyo

< 50 Bq/m^2 iodine-131 and cesium-137 was

No significant changes were reported in the 45 prefectures in gamma dose rates compared to yesterday.

IAEAアセスメント(4/5時点）

- On 5 April, low levels of deposition of both iodine-131 and cesium-137 were detected in 5 and 7 prefectures respectively. The values for iodine-131 ranged from 12 to 70, for cesium-137 from 3.6 to 41 becquerel per square metre.
- Gamma dose rates reported for 6 April showed no significant changes compared to yesterday. Since 23 March, values have tended to decrease. Gamma dose rates were reported for 45 prefectures to be between 0.02 to 0.1 microsievert per hour. In one prefecture the gamma dose rate was 0.16 microsievert per hour. These values are within or slightly above the natural background of 0.1 microsievert per hour.
- As of 4 April, iodine-131 and cesium-134/137 was detectable in drinking water in a few prefectures. All values were far below levels that would initiate recommendations for restrictions of drinking water. As of 6 April, one restriction for infants related to I-131 (100 Bq/l) remains in place as a precautionary measure in only one village of the Fukushima prefecture.
- On 6 April the IAEA monitoring team made measurements at 7 locations at distances of 23 to 39 km South and Southwest of the Fukushima nuclear power plant. The dose rates ranged from 0.04 to 2.2 microsievert per hour. At the same locations, results of beta-gamma contamination measurements ranged from 0.03 to 0.36 megabecquerel per square metre.

訳注：最新版はこちらから
http://www.iaea.org/newscenter/news/tsunamiupdate01.html

その他の核分裂生成物

- 他にも100種類近くの核分裂生成物がある。いずれもヨウ素やセシウムよりも重いが、爆発的事象により一部が拡散されたり、冷却水に混ざる可能性はある。
- 2号炉で推定されてる核分裂生成物リスト

Radionuclide Group	(kg)
Noble Gases (Xe, Kr)	361.8
Halogens (I, Br)	14
Alkali Metals (Cs, Rb)	207.8
Tellurium (Te, Se)	33.2
Alkaline (Ba, Sr)	154.1
Platinoids (ru, Pd, Rh)	234.3
Early Transition (Mo, Tc, Nb)	263.7
Lanthanides (La, Nd, Pr, Sm, Y, Pm, Eu, Am, Gd)	485.7
Cerium (Ce, Pu, Zr, Np)	1213.1

This is for a slightly larger reactor operating at lower enrichment

SAND2007-7697

プルトニウム

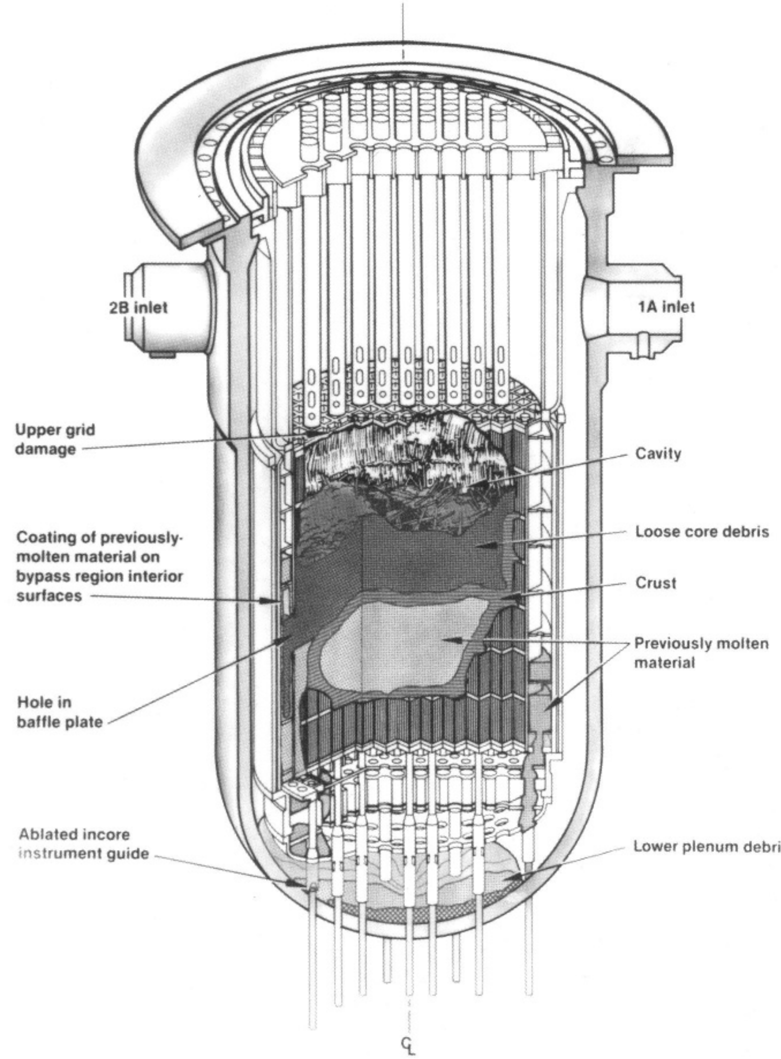
- Detected in soil near reactors
- Possible sources
  - Fallout from nuclear testing
  - Dispersed out of fuel by venting/explosions
    - By-product of U-238 absorbing neutrons
    - MOX fuel (6% of fuel assemblies in unit 2 contained plutonium)
  - Environmental contaminant from waste
- Not a health hazard – levels comparable with worldwide distribution of Pu from nuclear testing although significantly higher than previous samples at site.
- Preliminary analysis of 238/(239, 240) ratio indicates origin is fission by-product from normal reactor operation – another indication of breach of containment.
- Isotope ratio inconsistent with MOX fuel composition, solid waste, ordinary soil, or nuclear weapons testing
- Exceeding small amounts and further testing/confirmatory independent analysis is needed.

主な商業用炉での事故

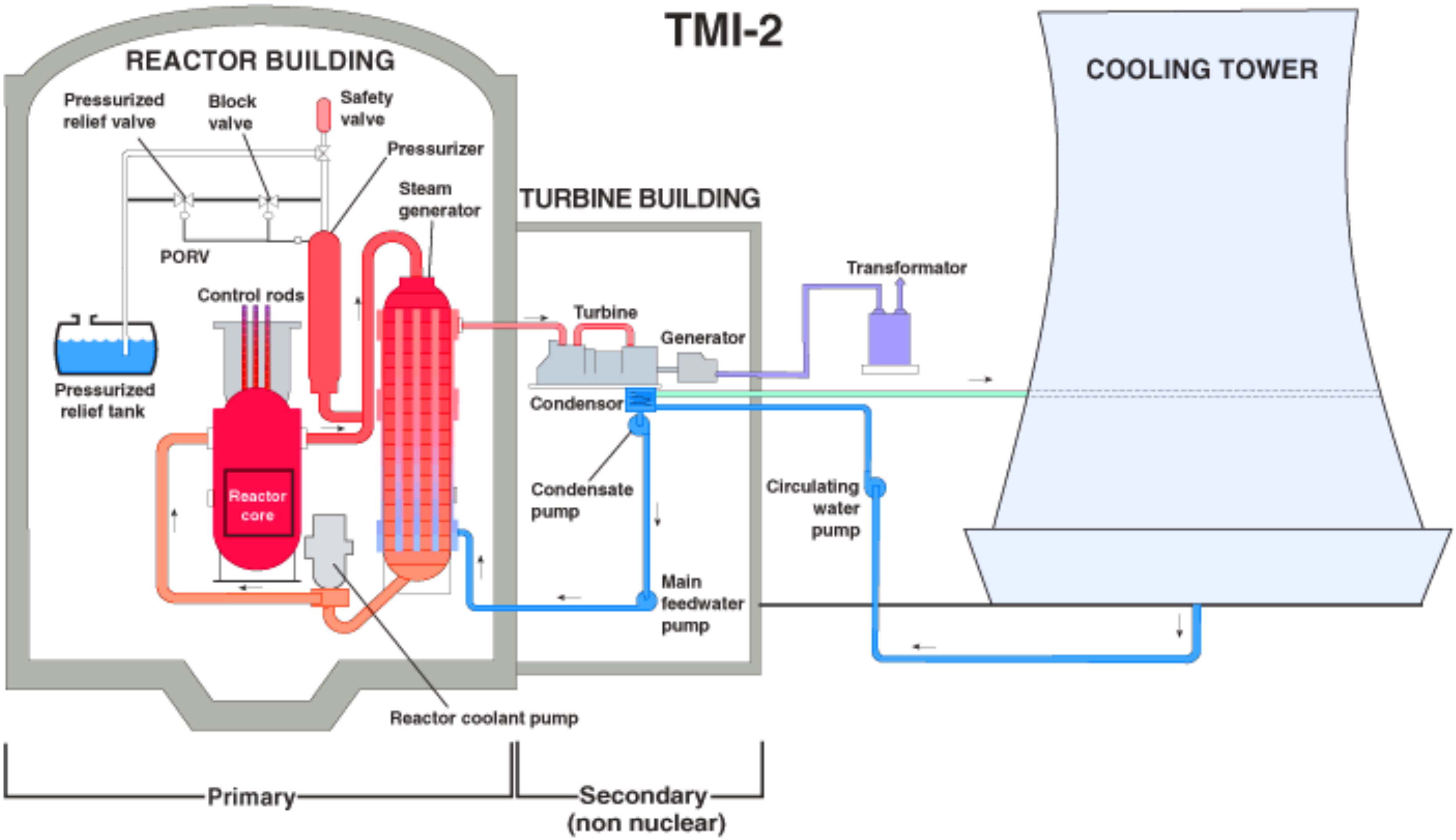
- Three Mile Island Unit 3 (1979)
- Chernobyl Unit 4 (1986)
- Fukushima Daiichi Units 1, 2, 3, 4 (2011)

スリーマイル島(TMI) ２号炉

- March 28, 1979
- 900 Mwe PWR
- Concrete containment
- Initiating event was interruption of feedwater
- Loss of coolant from stuck open relief valve
- Core badly damaged, nearly melted through lower head
- Hydrogen generation, explosion inside containment
- Minimal release of radioactivity
  - 20 person-Sv committed dose
  - 3.7×10^{17} Bq (10 Mci) total
  - 3×10^{17} Bq (8 Mci) of Xe-133
  - 1.8×10^{15} (57 kCi) Krypton-85
  - 5.5×10^{11} Bq (15 Ci) of Iodine-131
  - 3.8×10^{6} Bq (40 microCi) Cs-137



Wright, Advances in Nuclear Science and Technology, Volume 24, 283-314, 1996

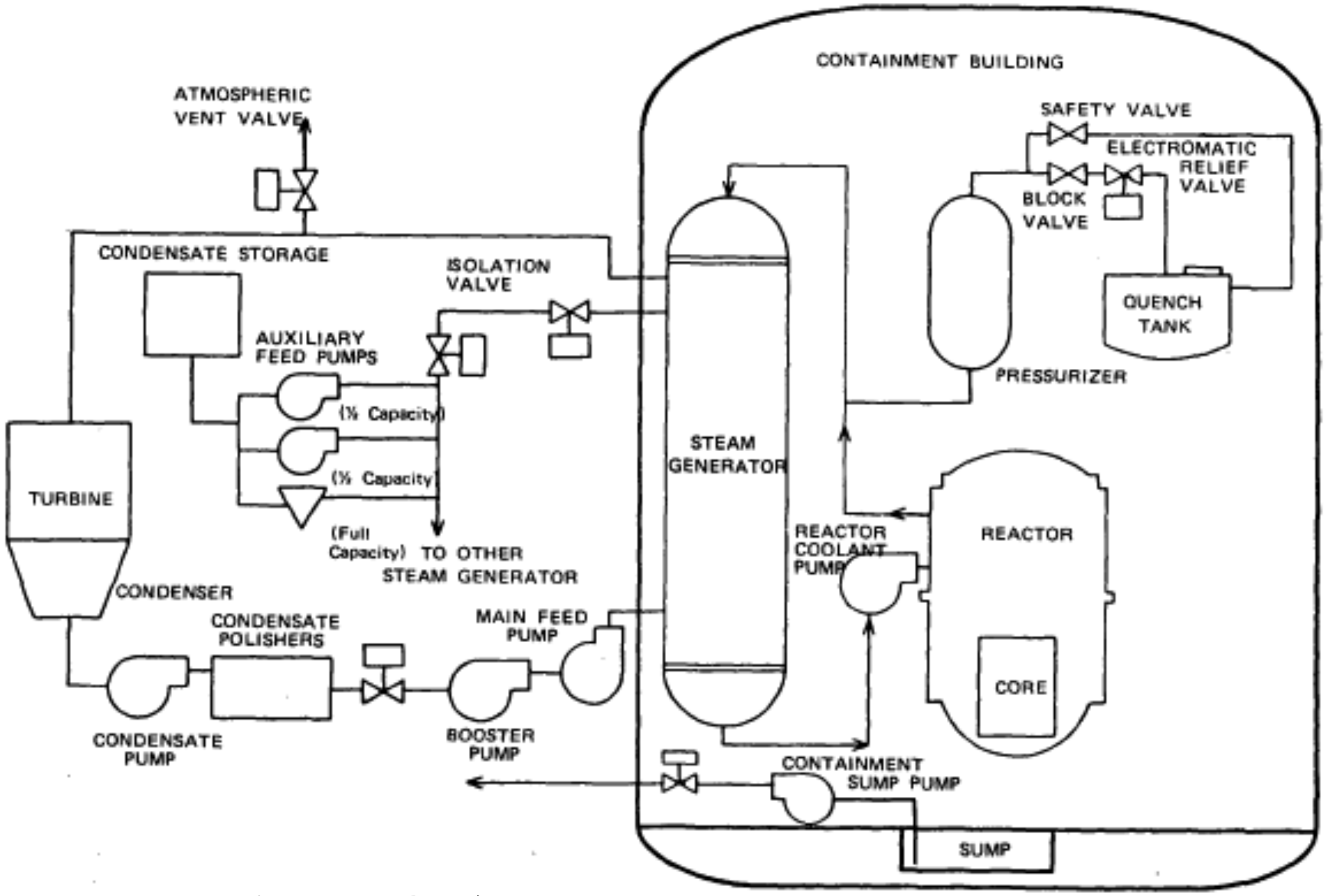


http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

何が起こったか？

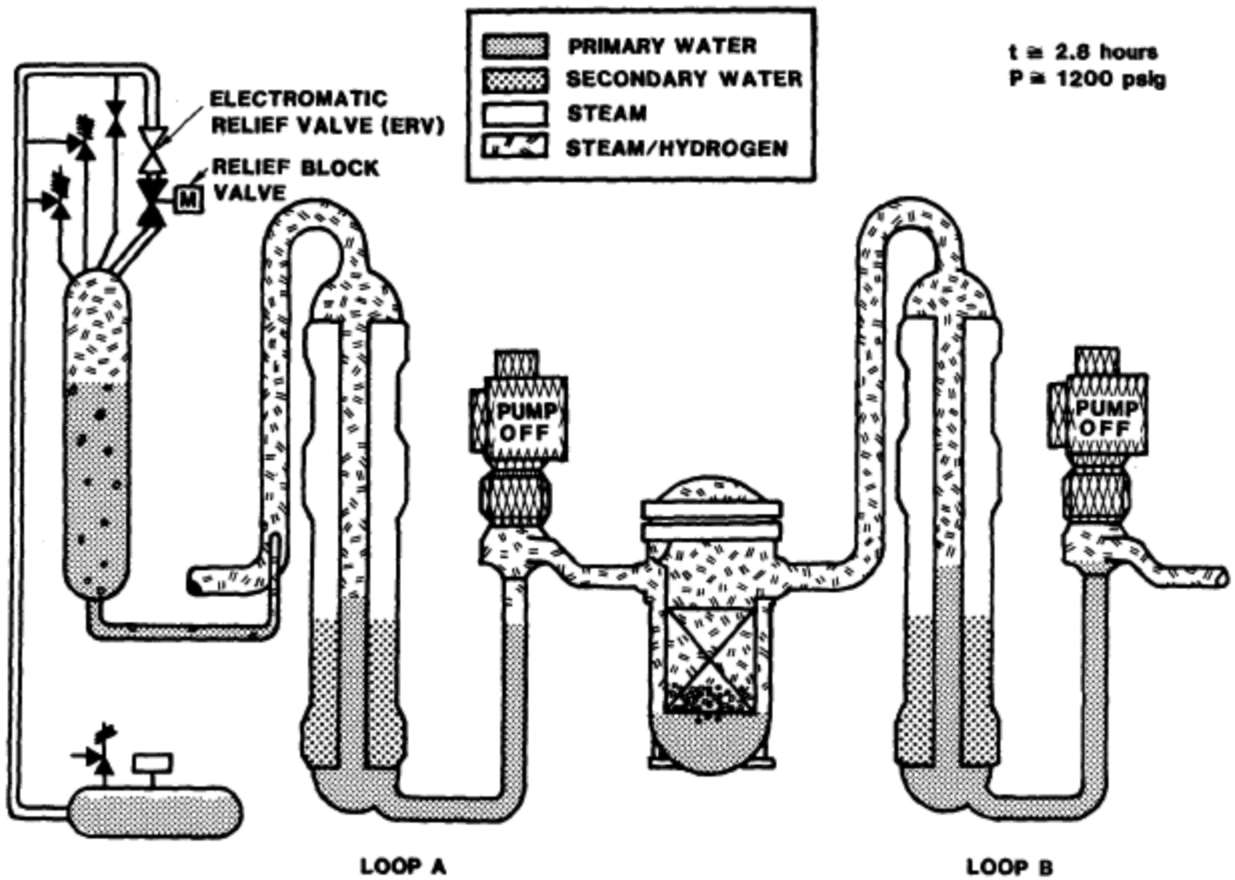
- Feed water interrupted
- Reactor scrammed
- ECCS pumps started/stopped
  - block valve closed, had to be opened by hand
- Heat exchangers boiled dry (2 min!)
- Pressure increased, relief valve opened automatically
  - Stayed stuck open for 2 hours
- ECCS pumped restarted then manually shut down
  - system appeared to be "solid"
- Core uncovered for at least 1 hr
  - 50% degraded, 20% in rubble bed at bottom of RPV
  - Hydrogen generation of 300-400 kg corresponding to oxidizing 45% of Zircaloy
- Water and H2 dumped into containment from PORV
- H2 (8%) burn in containment - 200 kPa pressure rise < 450 kPa design pressure (Henrie and Postma 1981 and 1987)
- Gaseous and volatile FP released accidentally and deliberately into atmosphere
- 14 year clean-up process, core removed & stored at INEL by 1990, 2.8 Mgal of contaminated water processed by 1993, required 1000 workers on site & $973 million

スリーマイル島の加圧水型原子炉 (PWR)



LWR H2 Manual NUREG/CR-2726

コアが一定期間露出した



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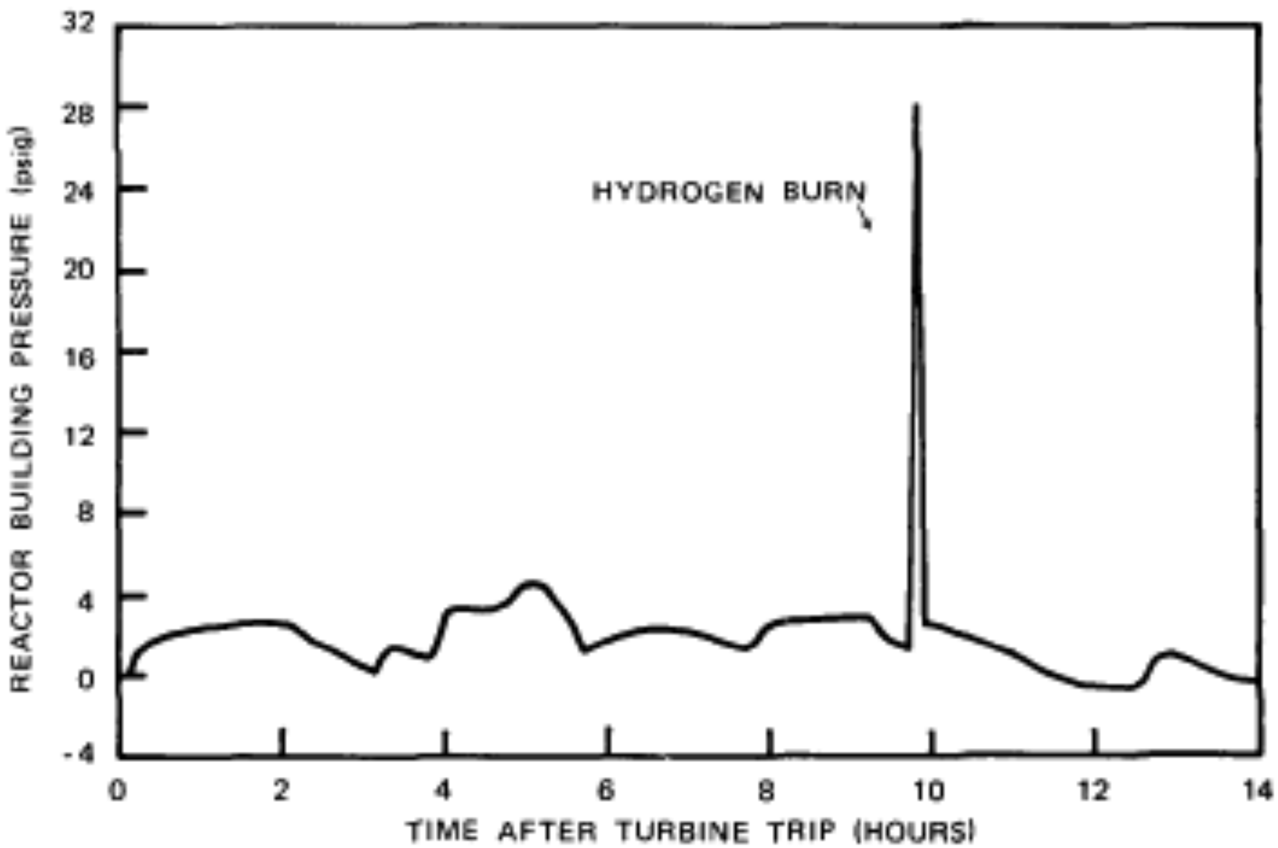
建屋内での水素燃焼



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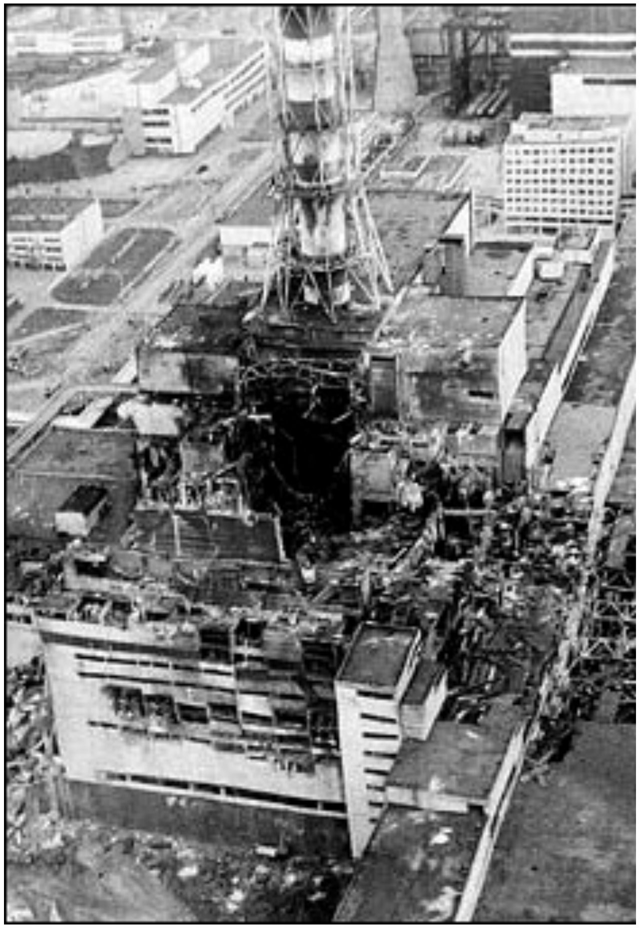
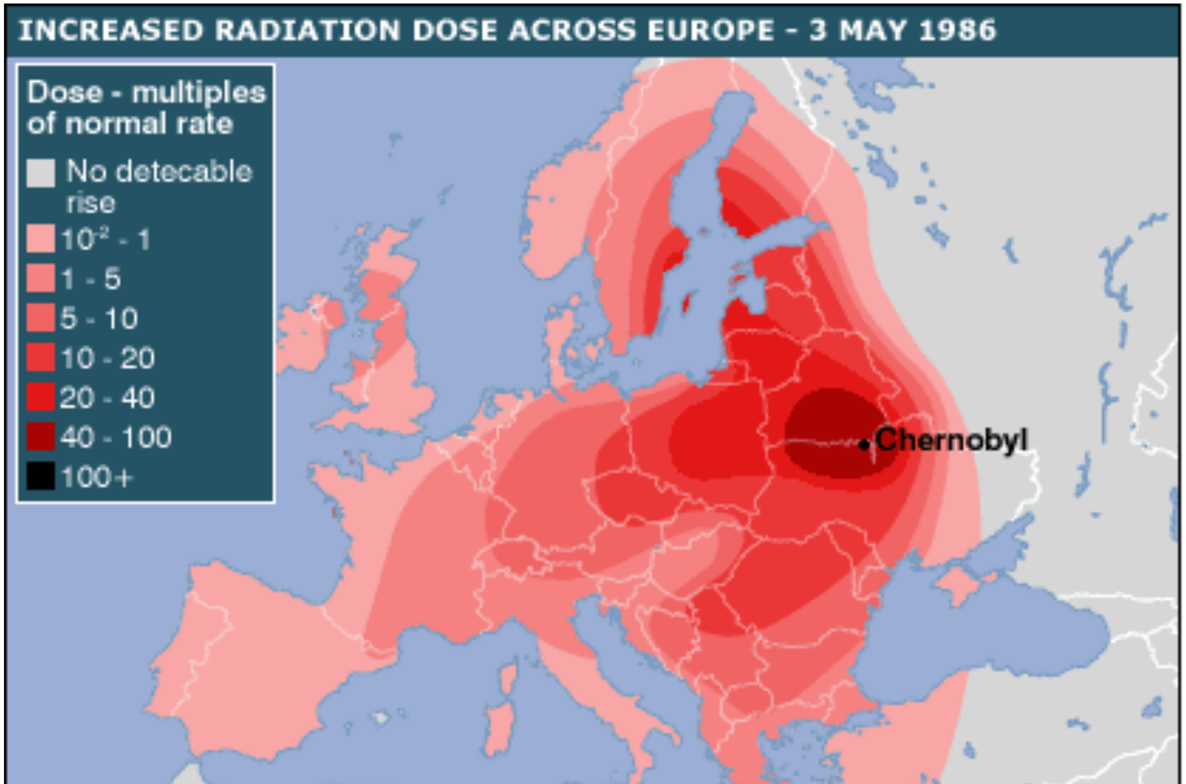
チェルノブイリ事故

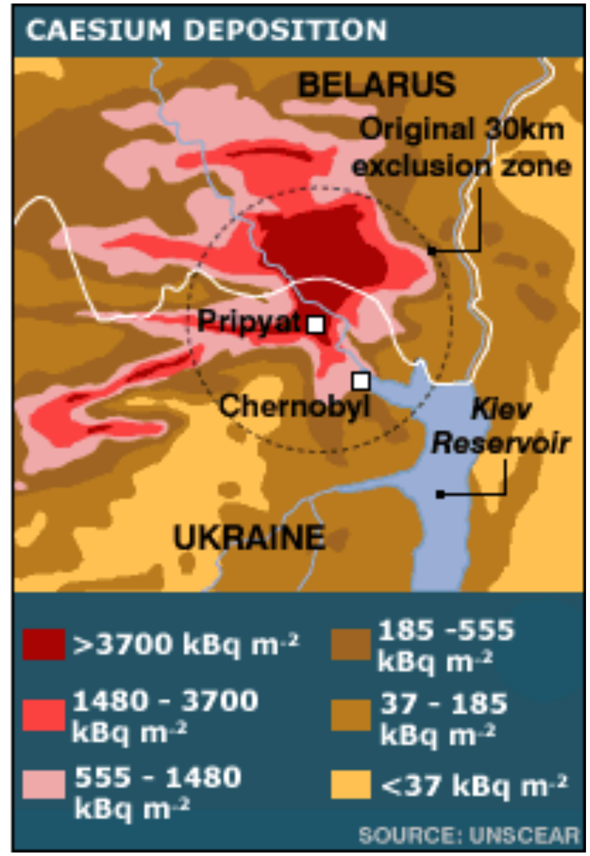


- 1000 Mwe RBMK-type reactor: Graphite-moderated, water-cooled, no containment structure or pressure vessel
- 26 April 1986
- Criticality accident caused by multiple factors including poor design, willful disregard of regulations, ignorance of reactor physics by operators
- Explosion and fire completely destroyed reactor, created large plume of contamination
- Required resettlement of 350,000 people
- 600,000 "liquidators" involved in cleaning up site and building containment structure.

石棺

- Remaining molten core materials (~200 tonne) enclosed in concrete "sarcophagus"
- 400,000 m^3 of concrete and 7,300 tonnes steel
- Deteriorating and cannot be repaired.
- 100-yr cover building to be installed in 2013





Species	Half-life	Released Amount	
		MCi	Bq
85Kr	10.8 yr	0.89	3.3×10^{16}
133Xe	5.2 dy	176	6.5×10^{18}
131I	8 dy	49	1.8×10^{18}
134Cs	2 yr	1.4	5×10^{16}
137Cs	30 yr	2.3	8.5×10^{16}
90Sr	29 yr	0.27	8×10^{15}

Cs-137 fallout

- 37 kBq/m² contaminated
- 555 kBq/m² restricted

UNSCEAR 2000

汚染およびに被害

- 10 mSv - 30 km exclusion zone, 116,000, all relocated
- 50mSv - Strict control zone, 270,000, some relocated
- 100 mSv – "Liquidators", 200,000
- 5 mSv – general population, 6,500,000
- Main contaminants are Cs-137 and Sr-90
  - 30 year half-life
- Collective dose commitment (2056) is 600,000 person-Sv
- Illness
  - 28 immediate deaths
  - 237 acute radiation syndrome
  - >4000 thyroid cancers from Iodine-131

3つの事故- それぞれ異なる状況

- スリーマイル島- 2号機
  - 1 PWR, reactor pressure vessel, containment building
  - Loss of coolant accident, 50% core damage, hydrogen explosion in containment
  - Pressure vessel, containment intact
  - Small release, no contaminated exclusion zone
  - Complete cleanup
- チェルノブイリ-4号機
  - 1 RBMK reactor, no pressure vessel and weak containment
  - Core and reactor building destroyed by critical disassembly
  - Release of substantial fraction of FPs including refractories during explosion/fire
  - Large contaminated zone (up to 100 km), reactor entombed
- 福島第一- 1ー4号機
  - 3 BWR reactors and 4 spent fuel pools, SBO
  - 30-70% core damage to 3 reactors, suspect RPV and PCV damage
  - At least 4 hydrogen explosions, severe damage to reactor buildings
  - Spent fuel fire suspected
  - Plant highly contaminated, substantial release of volatile FP
  - Extent of contaminated zone 20 km

Web上の情報

- http://www3.nhk.or.jp/nhkworld/

- http://www.nisa.meti.go.jp/english/
- http://www.tepco.co.jp/en/index-e.html
- http://www.jnes.go.jp/english/index.html
- http://www.jaif.or.jp/english/

- http://www.iaea.org/
- http://www.unscear.org/

- http://www.zamg.ac.at/

- http://www.world-nuclear-news.org/
- http://www.nei.org/
- http://www.new.ans.org/
- http://www.nucleartourist.com/

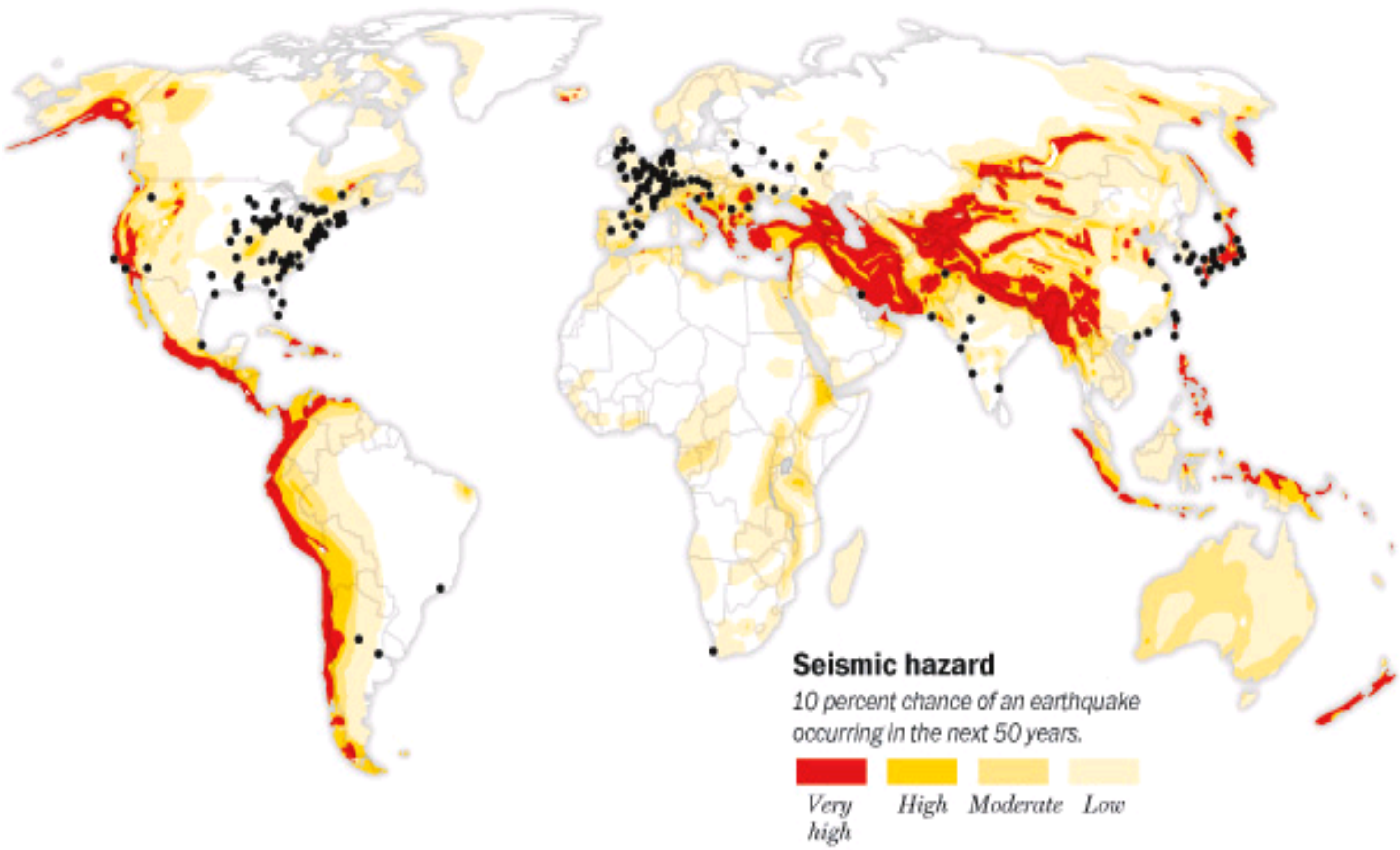
- http://www.nrc.gov/
- http://blog.energy.gov/content/situation-japan/
- http://www.epa.gov/radiation/
- http://www.ncrponline.org/

- http://en.wikipedia.org/wiki/Timeline_of_the_Fukushima_I_nuclear_accidents
- http://en.wikipedia.org/wiki/Fukushima_I_nuclear_accidents

原子力の今後の展望

- 世界規模の影響
  - 安全基準とリスク評価の大規模な再検討- チェルノブイリやスリーマイル島の時以上に
  - 核ルネッサンスが挫折
- 世界中にある〜440基の原発に重大な影響
- 経済的悪影響: 世界の電気の14%は原子力
  原子力発電のトップ3:
  - アメリカ、20% の電力 (101 GWe)
  - フランス、75% (63 GWe)
  - 日本、27% (47.5 GWe), 2030までに50%にする予定だった
- 原子力発電所停止の政治的圧力:ドイツ
- 原子力発電所維持の経済的圧力
- 原子力発電所の老朽化(アメリカでは40年のライセンスが終わり, 60年への延長の要求が)
- 技術者の課題:
  - 古い発電所を新しくするのは経済的か?
  - 新しいシステムは十分強固か?
- 社会的課題:
  - 電力のためどこまでリスクを負えるか？
  - 発電の維持も閉鎖も核廃棄物の収納を必要とする。どのようにこのプロセスを進めるか？

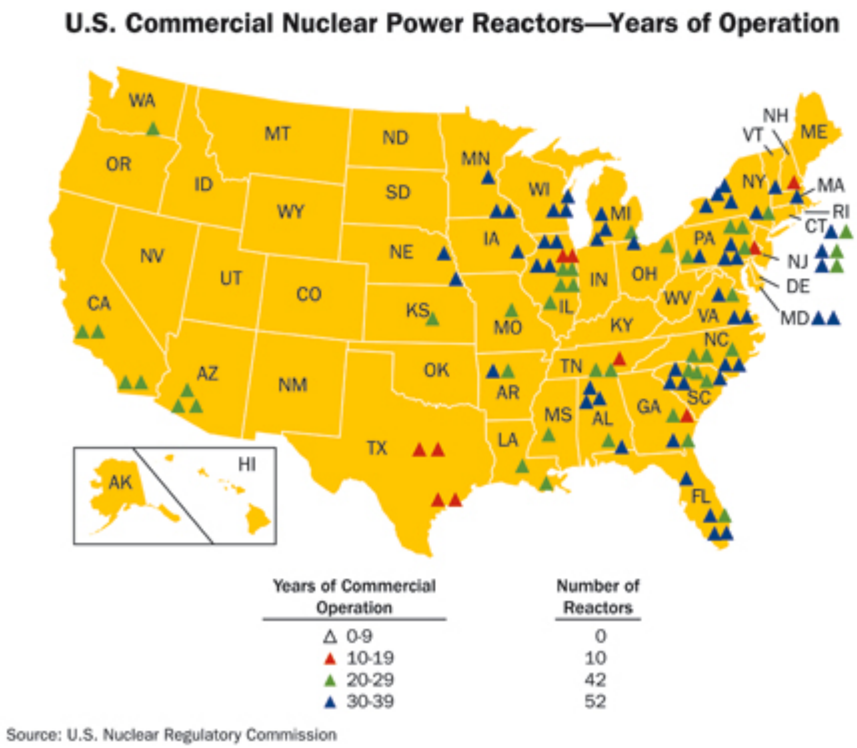
原子力と地震被害



NY Times

アメリカにある104の原子炉

- 23 are BWR Mark 1 containment type



Browns Ferry Nuclear Plant, Unit 1	AL	12/20/1973	5/4/2006	12/20/2033
Browns Ferry Nuclear Plant, Unit 2	AL	8/2/1974	5/4/2006	6/28/2034
Browns Ferry Nuclear Plant, Unit 3	AL	8/18/1976	5/4/2006	7/2/2036
Brunswick Steam Electric Plant, Unit 1	NC	9/8/1976	6/26/2006	9/8/2036
Brunswick Steam Electric Plant, Unit 2	NC	12/27/1974	6/26/2006	12/27/2034
Cooper Nuclear Station	NE	1/18/1974		1/18/2014
Dresden Nuclear Power Station, Unit 2	IL	2/20/1991	10/28/2004	12/22/2029
Dresden Nuclear Power Station, Unit 3	IL	1/12/1971	10/28/2004	1/12/2031
Duane Arnold Energy Center	IA	2/22/1974		2/21/2014
Edwin I. Hatch Nuclear Plant, Unit 1	GA	10/13/1974	1/15/2002	8/6/2034
Edwin I. Hatch Nuclear Plant, Unit 2	GA	6/13/1978	1/15/2002	6/13/2038
Fermi, Unit 2	MI	7/15/1985		3/20/2025
Hope Creek Generating Station, Unit 1	NJ	7/25/1986		4/11/2026
James A. FitzPatrick Nuclear Power Plant	NY	10/17/1974	9/8/2008	10/17/2034
Monticello Nuclear Generating Plant, Unit 1	MN	1/9/1981	11/8/2006	9/8/2030
Nine Mile Point Nuclear Station, Unit 1	MI	12/26/1974	10/31/2006	8/22/2029
Oyster Creek Nuclear Generating Station, Unit 1	NJ	7/2/1991	4/8/2009	4/9/2029
Peach Bottom Atomic Power Station, Unit 2	MI	10/25/1973	5/7/2003	8/8/2033
Peach Bottom Atomic Power Station, Unit 3	MI	7/2/1974	5/7/2003	7/2/2034
Pilgrim Nuclear Power Station	MI	6/8/1972		6/8/2012
Quad Cities Nuclear Power Station, Unit 1	IL	12/14/1972	10/28/2004	12/14/2032
Quad Cities Nuclear Power Station, Unit 2	IL	12/14/1972	10/28/2004	12/14/2032
Vermont Yankee Nuclear Power Plant, Unit 1	VT	3/21/1973		3/21/2012

US NRC