FILE: PBMR

Commissioner Briefing

NRC Delegation Visit to Germany on the Safety Aspects of HTGR Technology

August 22, 2001

Background to the Visit

Howard Faulkner, OIP

The NRC Delegation

Howard Faulkner - Office of International Programs

Stuart Rubin - Advanced Reactors Group, RES

Donald Carlson - Advanced Reactors Group, RES

Amy Cubbage - New Reactor Licensing Project Office, NRR

Undine Shoop - Reactor Systems Branch, NRR

Alex Murray - Special Projects Branch, NMSS

Meeting Agenda & Arrangements

Arrangements made by OIP and GRS

Agenda based on topics requested by NRC

Briefings involved representatives covering full breadth of German HTGR program:

- Julich Research Center
- Two reactor design/vendor organizations (Framatome ANP & Westinghouse HRB)
- Standards setting organization (KTA)
- Two organizations performing technical safety evaluations (TUV)
- State licensing authority for THTR
- Utility operating THTR (RWE Energie)
- A former member of the Reactor Safety Commission (RSK)

Location of Meetings

Two days at GRS in Cologne

Two days at the Julich Research Center

German representatives came from around the country for meetings

Most representatives participated for multiple days

HTGR Design and Technology

Stuart Rubin, RES

HTR Fuel Design, Development, Testing and Experience

- TRISO fuel particle is primary fission product retention boundary
- TRISO particle and pebble fuel element design and manufacture evolved over 30 years to a reference standard for use in German HTGRs
- Defective TRISO particles from manufacture dominates fission product release mechanisms during normal and off-normal reactor conditions
- Pebble Fuel element manufacturing process development achieved TRISO fuel particle defect rate specification of 6×10^{-5}
- Irradiation testing of reference fuel for german reactor design conditions showed <u>no</u> additional particle failures & low releases
- Irradiated Pebble fuel accident simulation (heatup) tests demonstrated low fission product release for predicted accident conditions
- Mechanistic Release model used for fission product source term
- Fuel for PBMR & GT-MHR will need to demonstrate equivalent performance

Graphite changes over time in a reactor component. Can grow or contract.

High-Temperature Reactor-Grade Graphite

- Graphite in HTGRs is used to fabricate fuel and core reflector structures

  – upper & lower core support struct

- Graphite functions include: neutron moderator, structural support, heat transfer and heat storage
- Safety issues arise due to irradiation effects graphite properties (e.g., strength, dimensional changes, conductivity, hot gas bypass leakage)
- Graphite development & testing in Germany resulted in suitable grades for German HTGR applications, behavioral predictability & satisfactory performance
- Graphite feed sources for these graphite grades may no longer be available
- New graphite feed sources and grades will need to be developed, irradiated and tested for use in the PBMR and GT-MHR

Pebble Bed Reactor Core Heat Transfer and Fluid Flow

- Fuel maximum steady-state temperature and peak accident temperature must stay within design limits to assure fuel integrity basis

- Experiments and analytical model and methods development were conducted to predict heat transfer and temperature distributions in pebble bed cores (e.g., in coated particles, pebbles, pebble-to-coolant, between pebbles)

- HTR-Modul predicted accident temperatures showed passive reactor shutdown, and effective passive decay heat removal with fuel, vessel wall and reactor support structures within the design envelope.

- Pebble Melt-wire tests conducted at AVR for normal operation indicated that calculated maximum local core temperatures were non-conservative.

- Large scale model tests have been conducted to validate the analytical models and methods that are used to calculate radial and axial core temperature distributions in modular HTRs due to decay heat transfer during accidents.

- signal Δ between predict flow & actual results.

THTR Core Pebble Flow and Safety Impacts

- Pebble bed reactor fuel pebbles flow slowly down through the core like sand flows down through an hour glass.
- Experiments have been conducted to develop analytical models and methods to predict pebble flow distribution in the core.
- Analysis for THTR operations showed the actual pebble flow distribution was significantly different than predicted distribution.
- Pebble flow distribution errors impacted operational and safety-related core characteristics: core power distribution, core temperature distributions, reactor system mechanical loadings; nuclear shutdown margins.
- PBMR pebble flow distribution prediction will be considered in the PBMR reviews and flow distribution errors would need to factored into design and safety analyses.

Jülich Research Center Experimental Facility Tour

- Tests show graphite pebbles rapidly oxidize in air at accident temperatures

  Various silicon carbide protective coatings are being investigated as potential "next generation" pebble fuel designs to prevent exothermic pebble oxidation

- Large scale model tests showed convective air flow through an HTR-Modul core will begin several days after a large RCPB break if no actions are taken

  Air-induced oxidation can be limited if break is sealed or confinement structure limits air ingress

  ESKOM is evaluating applicability of test results to PBMR design and potential remedial actions

- Radiological source term would be significantly impacted in the event of oxidation and air flow through the PBMR core

- Potential air flow through and oxidation of the core are areas of focus for the PBMR pre-application review.

German HTR Codes and Standards

- KTA Codes and Standards were prepared in final form and in many cases draft form for use in German HTGR design and safety reviews.
- Many design aspects are addressed such as: high temperature metals, reactor core nuclear design, graphite components, pebble heat transfer, helium use.
- Most were never endorsed by regulatory authorities due to decline in German HTGR nuclear power program funding
- HTR-Modul safety assessment used the KTA codes and standards for identifying HTGR-specific safety requirements where LWR safety requirements did not apply.
- Germany no longer supports HTGR codes and standards development
- KTA HTGR codes and standards will be translated and distributed for technology reference and potential use in identifying design-specific requirements for the PBMR and the GT-MHR designs

AVR Operating Experience, Lessons Learned

Donald Carlson, RES

AVR Operation, Testing, Lessons Learned

AVR: Pebble-Bed Test Reactor, 15 MWe, Operated 1967-1988 Capacity ~50%

Shulton Reactor

AVR Operating Experience and Events - Highlights

- Fuel Handling System Required Modification to Address Frequent Maintenance
- Graphite Dust Accumulation due to Abrasion of Pebbles
- 1979 Water Ingress from Steam Generator Leak, No Fuel Damage
  tons of water got into the system
- Coolant Activity Monitoring for Performance of Developmental Fuels
- Graphite Reflector Structures in Good Condition after 21 Years Operation

AVR Operation, Testing, Lessons Learned (Continued)

AVR Testing Program Highlights

Melt-Wire Experiments Showed Unpredicted Core Hot Spots at Power:

- Ongoing Re-Analysis by Jülich Research Center:
  - Implications for code validation/correction in predicting maximum fuel operating temperatures
  - Implications for similar measurements needed in future reactors

This issue has been discussed with Eskom & the max fuel operating temperatures have been modified.

Demonstration of Modular HTR Safety Principles:

- Simulation of Pressurized & Depressurized Loss of Forced Cooling Without Scram

AVR Provided Large-Scale Irradiation Testing of Pebble Fuels, including the HTR-Modul TRISO Fuel Design

German HTR Safety Assessments
and
THTR Operating Experience

Amy Cubbage, RES

THTR - Safety Assessment

1971 THTR Construction Started - Technical Rules and Guidelines did not Exist for THTR Concept

1977 Safety Criteria Went Into Effect for all Reactor Types - HTR Specific Characteristics were not Considered

1978 Reactor Specific Interpretation of Safety Criteria was Developed ("THTR-Planning Basis")

1980 HTR Safety Criteria Developed Which Provided More Precise Technical Requirements

- External Impact (Aircraft, Pressure Wave, Earthquake, Etc.)
- Internal Impact (Pipe Whip, Etc.)
- Radiation Protection

[illegible] U.S. design basis scenarios?

"Backfits" Were Required During THTR Construction to Address Evolving Requirements

1985 Commercial Power Generation

Licensing Process was Much Longer than Anticipated (>14 Years)

THTR - Operating Experience/Lessons Learned

Operational/Design Problems: - Capacity factor 60-70% . availability.

- Broken Pebble Fuel Elements (~17,000 pebbles) due to In-Core Control Rod Insertion (Coated Fuel Particles Remained Intact)
- Observed Pebble Flow Profile Significantly Different than Predicted
- Core Helium Bypass Flow Significantly Different than Predicted (18% vs. 7%)
- Bolts in the Thermal Insulation in the Hot Gas Ducts were Damaged due to Larger than Expected Thermal Gradients
- Larger Quantities of Graphite Dust in Primary System than Anticipated, Inadequate Filtration led to offsite radiological release

German Parties did not View these Problems to be Significant Technical or Safety Issues

THTR Shut Down Prematurely Four Years After Licensing

- Increased Estimate of Potential Financial Risk
- Unfavorable Political Climate Following Chernobly Accident and Rise of Green Party

HTR-MODUL Safety Assessment

80 MWe Modular Pebble Bed Reactor Design - Similar in concept to PBMR

- State of lower Saxony.

Application for Site-Independent Concept License submitted by HTR GmbH in 1987

LWR Technical Rules and Guidelines and Limited HTR Codes and Standards were Available for the Design and Safety Assessment

Comprehensive and Consistent set of Design and Evaluation Criteria developed by screening Existing LWR Requirements and Adding Concept Specific Requirements

TÜV Performed Traditional Deterministic Review Against Basic Safety Criteria:

- Shutdown (Diverse Systems)
- Decay Heat Removal (Passive Core Heat Removal)
- Fission Product Retention (Fuel Elements and Vented Confinement)

Licensing Basis Events (LBEs) were Screened for Completeness and HTR-Modul Specific Scenarios were Added

HTR-MODUL Safety Assessment (Continued)

Safety Analysis Revised by Applicant to Address Additional LBEs and to Include Conservative Assumptions such as Single Failure and No Credit for Non-Safety Related SCCs

Revised Safety Analyses Resulted in:

- Increased Fuel Design Temperature from 1600 °C to 1620 °C
- Design Changes to Reactor Protection System
- Changes to Seismic Design

Application was Withdrawn for Political Reasons in 1989

TÜV Completed Assessment and Provided Final Report to Reactor Safety Commission (RSK)

Conclusions of Safety Assessment:

- Concept suited to comply with German Licensing Requirements
- Design has Favorable Properties even in the Range of Beyond Design Basis Events
- With Respect to Safety a License Could Have Been Granted with Additional Requirements

HTR Nuclear Materials Safety

Alex Murray, NMSS

HTR Nuclear Materials Safety

(Separate Handout)

Know-How Transfer
From Germany to ESKOM

and

Overall Conclusions

Stuart Rubin, RES

Know-How Transfer From Germany to ESKOM

- German organizations with a core of HTR technical expertise have archives of technical documents on German pebble bed reactor R&D, design, testing, operation, SARs and SERs.

- Owner of HTR [illegible] design — Reg expertise — expertise in fuel manufacturing

- Julich Research Center, HTR GmbH, TUV-Hanover and NUKEM have signed agreements with ESKOM to provide their technical information and selected assistance to support PBMR licensing in South Africa.

- NRC cooperation with the involved organizations in support of PBMR review in these technical areas would likely create a conflict of interest for the organizations

- Agreements prohibit ESKOM (or the other involved receiving organizations) from providing the technical information to third parties (e.g., NRC)

- Some of the German organizations have indicated that the technical information provided to ESKOM and PBMR, Pty., as well as technical support, could be provided to NRC under separate agreements.

Conclusions from the Trip to Germany

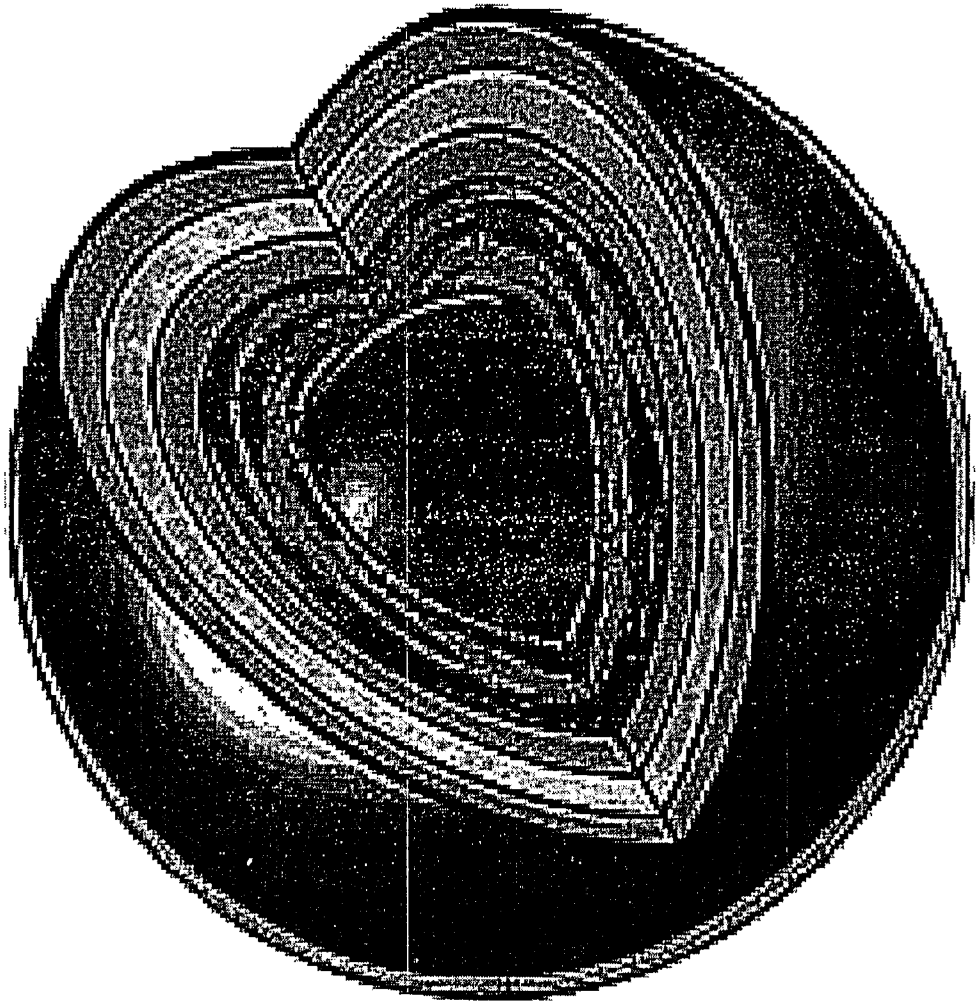
- The German nuclear power industry believes they have demonstrated that HTRs can be successfully designed, constructed and licensed, and operated with acceptable safety performance.

- German safety and regulatory authorities believe that the HTR-Modul design (a modular pebble bed reactor similar tp the PBMR) would be able to meet the safety criteria for licensing in Germany.

- German HTGR operating experience shows that startup problems with new HTGR plant designs can be expected.

- German experiments, plant operations and tests show that important HTGR design, technology and safety analysis issues exist and will need to be investigated and resolved before licensing an HTGR in the US.

- German HTGR information, expertise and experience will be valuable in supporting NRC HTGR infrastructure development for HTGR safety reviews.



- Process & fission release driven by fuel manufacture quality.
- · Defects 1 particle in 4-5 pebbles

  1×10^{-6}.

  6 defects per 100,000
- No fuel failures above the random defect rate.

- Have very good radionuclide source term models.

It is a dominant source term under within the regulatory stds for release

Heute besteht der AVR-Kern zu 50% aus Brennelementen mit niedrig angereichertem Uran und hohem Plutoniumanteil. Das transiente Verhalten ist unverändert gut (Abb. 5). Eine Vielzahl von statischen und dynamischen Experimenten wurde durchgeführt und erfolgreich nachgerechnet. Exemplarisch seien hier die Versuche mit ausgewählten LEU-Brennelementen erwähnt, die wohldefiniert einmal den zentralen Kern durchliefen und deren Spaltstoffzusammensetzung dann in Seibersdorf analysiert wurde. Die Vorausrechnungen mit AVR-adäquaten Rechenprogrammen wiesen selbst bei den Plutonium-Isotopen nur Abweichungen von weniger als 5% auf.

Für die Erprobung der Programme zur Thermohydraulik war der AVR-Kern ebenfalls gut geeignet. Es gelang dabei auch, die Kopplung zwischen den reaktorphysikalischen und thermohydraulischen Vorgängen gut zu simulieren und zu überprüfen. Besonders mit dem Rechenprogramm TINTE können die dynamischen Experimente bei verschiedenen HEU/LEU-Verhältnissen, ausgelöst durch Stabfahren oder Änderung des Kühlgasmassenstromes, zweidimensional gut berechnet werden. Auch die beobachteten, z.T. sehr hohen Maximaltemperaturen im Kern können mit den Rechenmodellen weitgehend erklärt werden. Hier sind allerdings noch detaillierte Untersuchungen erforderlich.

4.3.3 Meßtechnik

Im Rahmen des Versuchsprogramms bis Ende 1988 wurden große Anstrengungen unternommen, Temperaturen und Neutronenflüsse im und am Reaktorkern besser zu erfassen:

- Durch das Mannloch des äußeren Reaktordruckbehälters wurden auf Corehöhe im Sperrspalt 60 Thermoelemente installiert, die während des Versuch zum Kühlmittelverlust zulässige Temperaturen nachwiesen.
- Kombinierte Thermoelement/Rauschthermometrie in einer Lanze verbesserte die Informationen im Deckenrefelektorbereich. Dieses System wurde am AVR inclusive einer Datenfernübertragung für den betrieblichen Einsatz handhabbar gemacht und erprobt.
- Japanische Spaltkammern mit Einsatztemperaturen bis zu 850°C wurden in das stillgelegte Dampferzeugertragrohr abgelassen. Die damit gewonnenen thermischen Neutronenflüsse liegen zum Teil erheblich über

from: "AVR-20 Jahre Betrieb," VDI Berichte 729, VDI Verlag (1989)

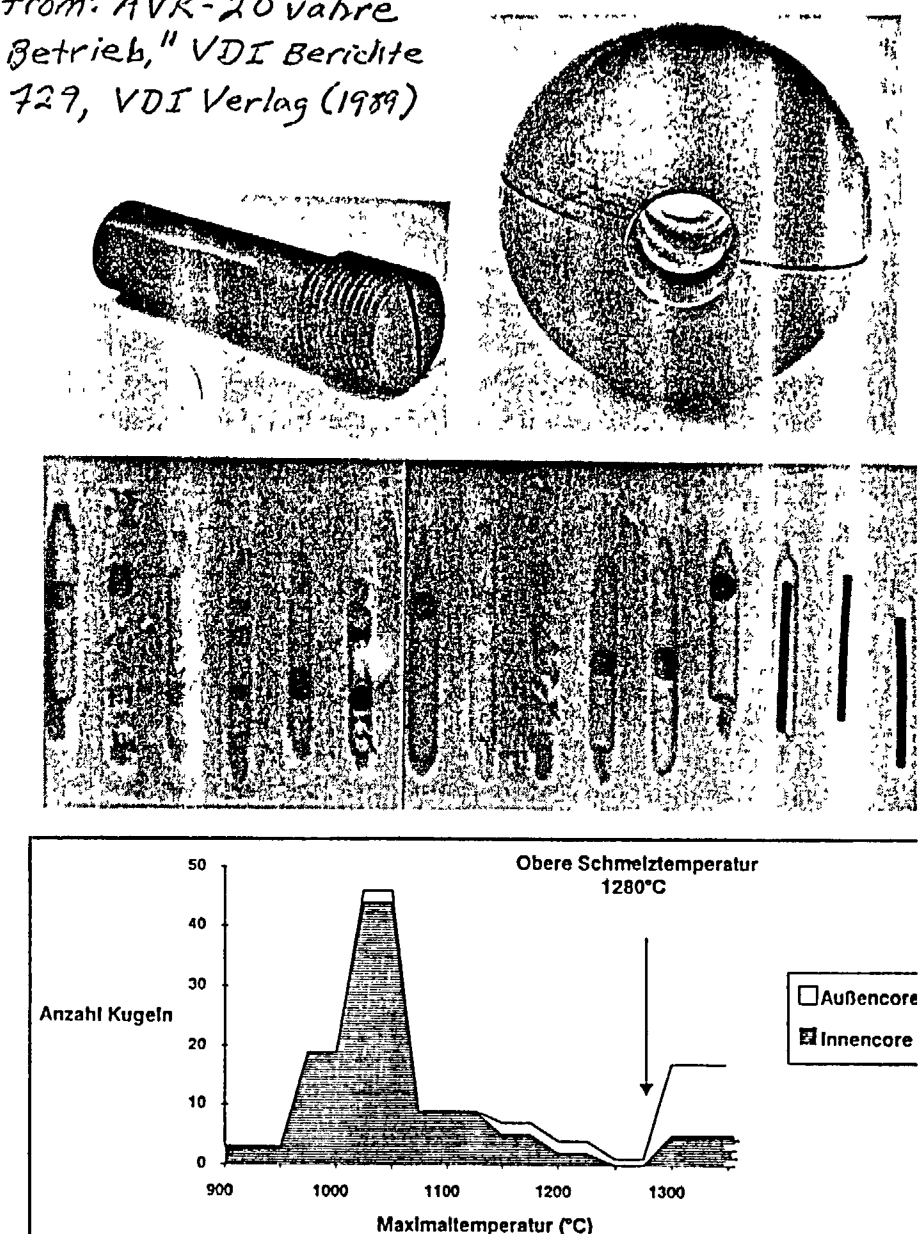
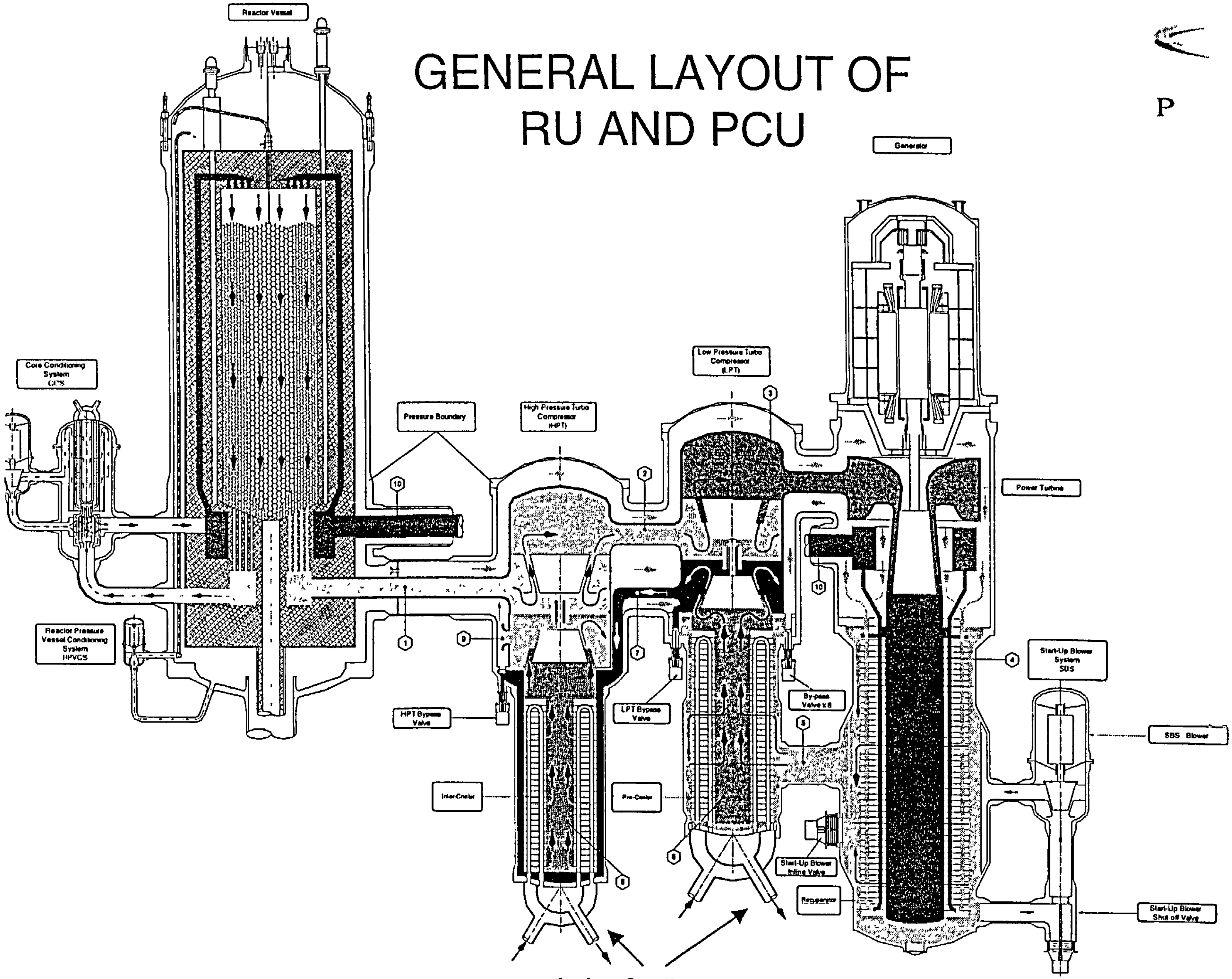


Abb. 6: Temperaturmeßkugeln (oben) mit 20 Schmelzdrähten (Ausschnitt aus Röntgenaufnahme, Mitte) zeigten teilweise unerwartet hohe Temperaturen (unten).

GENERAL LAYOUT OF RU AND PCU

P B M R



Active Cooling System

HTR Fuel Cycle Insights and NMSS Topics - from Trip to Germany

Alex Murray
Special Projects Branch
NMSS/FCSS

Major Findings

* Near-term: 0 - 5 years

* Mid-term: 2 - 10 years

Near-Term Findings

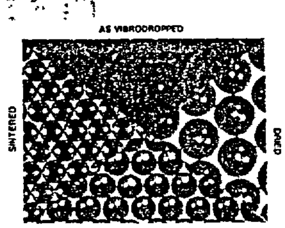
Findings:
* Fuel reliability from testing
* SNF handled by metal casks

NRC/NMSS Thoughts:
* Fuel fab to meet fuel reliability/QA/QC
* SNF and waste (C-14, adsorbent dust), voids, packing
* Transportation of new fuel (> 5% assay)/containers
* Address failed pebbles/particles new/irradiated
* MC&A/Safeguards

Fuel Reliability/QA/QC

Findings:
* 25 year program for fuel development
* SiC main coating
* Extensive fuel characterization needed

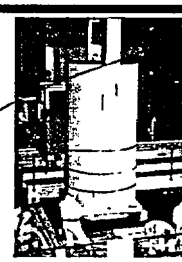
NRC/NMSS Thoughts:



* For new HTRs, new fuel fab needed (overseas?)
* Larger output than German demo. fuel plant
  - more lines?
  - bigger equipment?
* No extensive fuel development for 10+ years

Spent Nuclear Fuel - SNF

Findings:
* Low power densities
* Prone to movement
* Metal casks, inner cans with seals
* Packing in air (no He), CASTOR casks, monitors



Spent fuel assemblies ... Not helium

NRC/NMSS Thoughts:
* Larger physical/volumetric quantities
* Different from LWR oxides
* Probably weld, He in U.S.
* No pebble, NRC licensed S/T casks in US
* Return SNF? DOE?
* Criticality code validation for >5%

**** Potential > 10 fold increase in SNF volume***

may be a factor of 20

Julich THTR 40% packing efficiency ...

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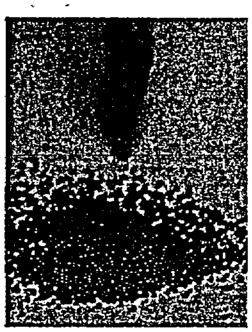
Mid-Term Findings 2-10 years

* Depends on degree of deployment of HTRs/PBMRs



If significant deployment:
* Domestic fuel cycle
* SNF treatment/repository effects
* Licensing for enrichment and fuel fab.
* More flammables, chemicals in fuel fab.
* Higher assay - enrichment, safeguards?
* Trapped/"lost" pebbles, D&D

*** > 5% assay commercial facilities not yet licensed**

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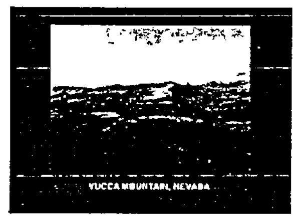
AVR 500 tons of irradiated graphite.

Mid-Term Findings for SNF

* Proposed repository thermally limited
  * Larger-scale HTR/PBMR deployment could impact repository volume limits
    * SNF could be processed to reduce volume
      * Further testing/analyses would be needed for repository operations/disposal, C-14?
        - leach, fire, handling tests
        - criticality/modeling/performance of pebble SNF

*** Probably > 500 te irradiated graphite per 100 MWe module**



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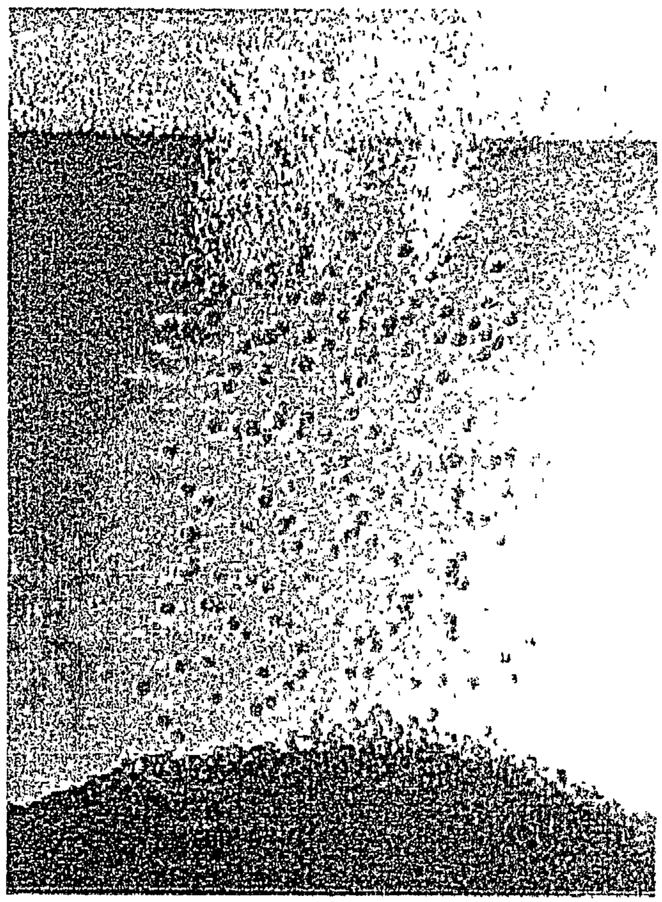
- For UK reactors initial proposal is 100 year schedule. Now decision to reduce this to 50 years

- For the Hanford reactors, we're keeping [them] entombed. - 50 years +.

Ft St Vrain Graphite went to Idaho

Vibrodropping Operation



* Nozzles above surface

* Must have sufficient drop height for spheres to harden

* Particles must age - ADU reactions - before drying

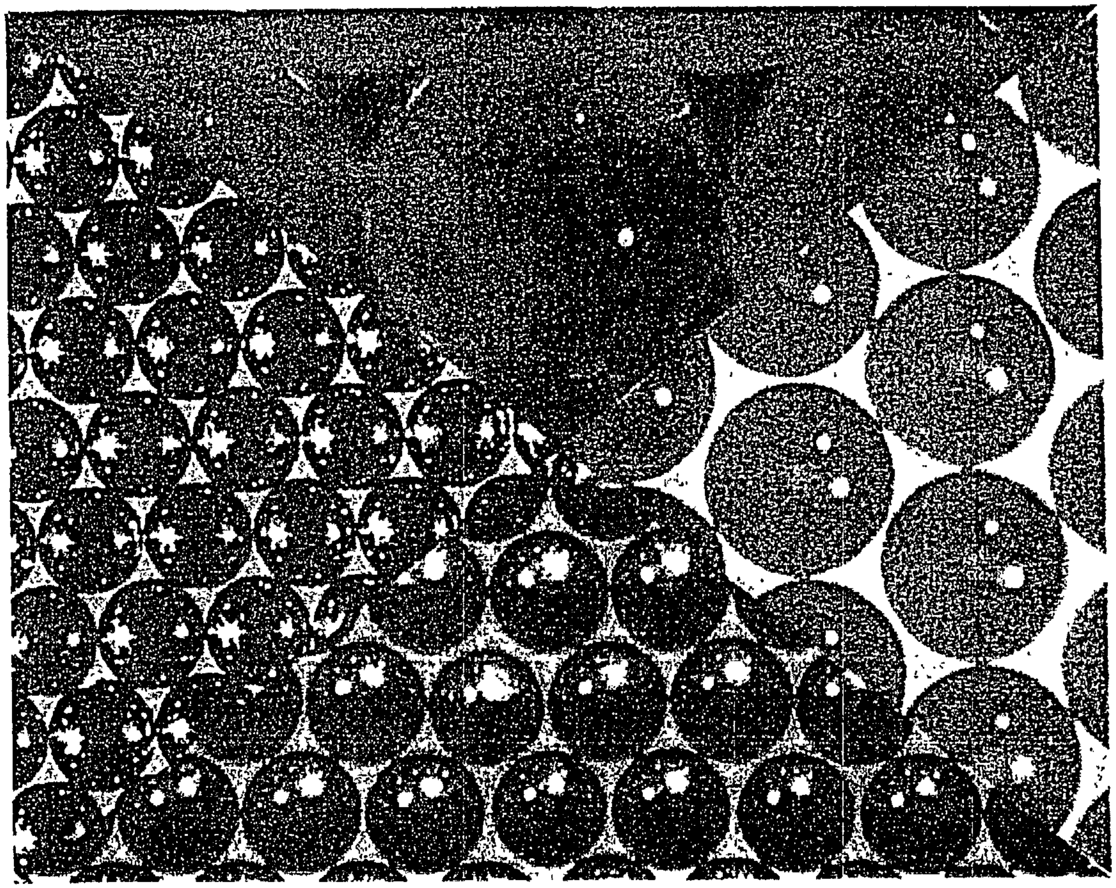
* Dimensions continually decrease

Aging mass of kernels at bottom of reservoir

The Particles

AS VIBRODROPPED

SINTERED

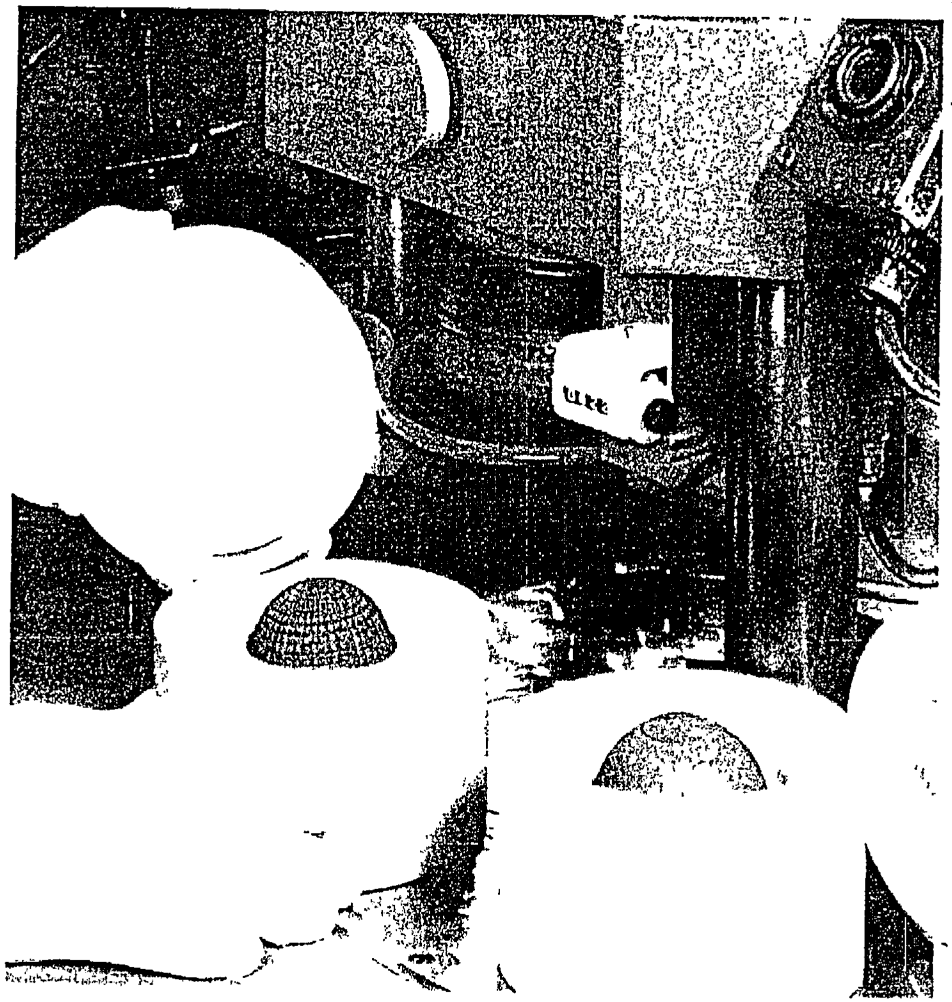


DRIED

CALCINED

* Approx. 30X
* Sintered spheres about 0.5 mm

Pebble Photographs

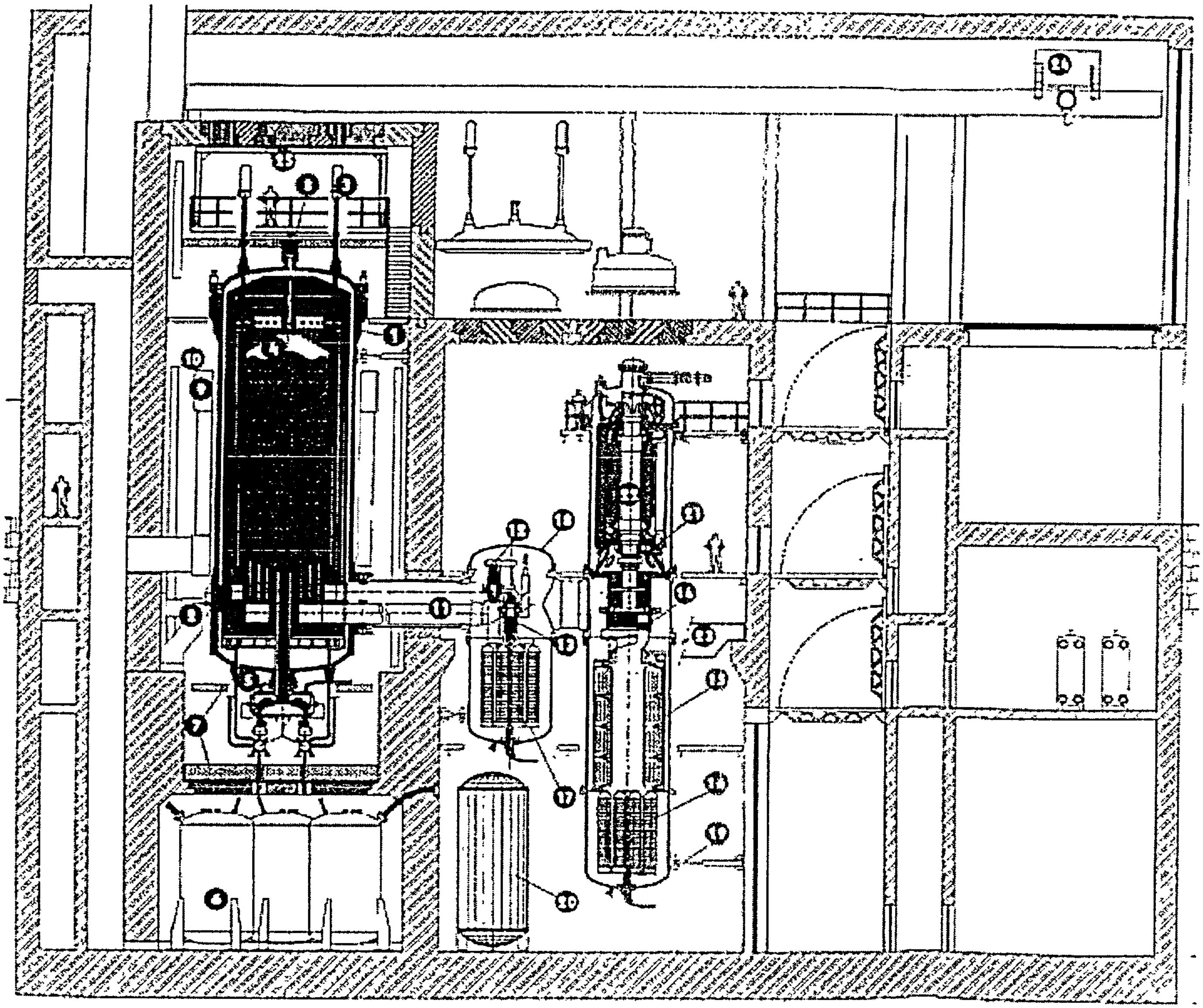


* LHS - fuel core
  Note striations for better adhesion

* RHS - fuel pebble; fuel core with fuel free graphite layer added (smooth)

* Isostatic ("even") pressing in silicone rubber moulds

Pebble Bed Modular Reactor



1 = reactor vessel	2 = reactor vessel support	3 = control rod drive mechanisms
4 = fuel	5 = defuelling devise	6 = spent fuel storage vessels(7)
7 = radiation shield	8 = seismic support	9 = heat removal skirt
10 = reactor pit cooling	11 = main connection manifold	12 = turbine comp. No 1
13 = turbo comp. no 2	14 = power turbine	15 = recuperator
16 = precooler	17 = intercooler	18 = power conversion unit enclosures
19 = snubbers	20 = helium storage tanks (9)	21 = generator coupling
22 = generator	23 = main carrier beam	24 = main overhead crane