HTGR SAFETY RESEARCH PROGRAM

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ABSTRACT

An HTGR safety research program is being performed supporting and guided in priorities by the AIPA Probabilistic Risk Study. Analytical and experimental studies have been conducted in four general areas where modeling or data assumptions contribute to large uncertainties in the consequence assessments and thus, in the risk assessment for key core heat-up accident scenarios. Experimental data have been obtained on time-dependent release of fission products from the fuel particles, and plateout characteristics of condensible fission products in the primary circuit. Potential failure modes of primarily top head PCRV components as well as concrete degradation processes have been analyzed using a series of newly developed models and interlinked computer programs. Containment phenomena, including fission product deposition and potential flammability of liberated combustible gases have been studied analytically. Lastly, the behavior of boron control material in the core and reactor subcriticality during core heatup have been examined analytically. Research in these areas has formed the basis for consequence updates in GA-A15000. Systematic derivation of future safety research priorities is also discussed.

INTRODUCTION

The Accident Initiation and Progression Analysis (AIPA) study led to several safety R&D recommendations (Ref. 1). These recommendations were systematically obtained on the basis of relative risks predicted for the dominant accident scenarios (core heatup) and the major sources of uncertainty associated with those predictions. The four separate studies support the core heatup consequence assessments as follows:

1. Fission product release study failure of fuel particle coatings, fission product release from the fuel and transport to the containment, and plateout processes within the PCRV.

2. PCRV integrity study - physical processes associated with primarily tophead PCRV component failure modes and degradation of the concrete.

3. Containment Atmosphere Response (CAR) study - natural deposition of released fission products, pressurization due to gas accumulation, potential flammability of combustible gases, and effects of helium blowdown jets.

4. Recriticality examination - migration of boron carbide control material and associated reactivity effects and shutdown margins.

Research in these areas to date formed the basis for the updated consequence assessment of the AIPA study documented in GA-A15000 (Ref. 2). The present status and technical accomplishments of these tasks are discussed in this paper.

FISSION PRODUCT RELEASE AND PLATEOUT

The release rate of fission products from the fuel particles and the plateout of activity on PCRV surfaces during core heatup were found to be important parameters that contribute significantly to the fission product releases predicted over the spectrum of core heatup scenarios.

In laboratory furnace tests, the release of fission products was measured from laser-failed irradiated BISO ThO_2 and TRISO UC_2 fuel particles over a range of burnups. The burnups were 0.25, 1.4 and 15.7% FIMA for ThO_2 particles and 23.5 and 74% FIMA for UC_2 particles. The fission products measured were nuclides of xenon, iodine, krypton, tellurium, and cesium.

Two types of experiments were performed: isothermal and temperature rise experiments. The range of the temperatures was from 1200°C to 2300°C. In the temperature rise experiments, the heating rates were between 50°C and 450°C/hr. The isothermal experiments provided a basis for developing a release model and the temperature rise experiments provided a test for the model in describing the release in a core heatup event. Good agreement was obtained between the model results and test data from the temperature rise experiments. Detailed results are documented in Ref. 3.

The central feature of the developed release model is a fractional release function which describes the release as a function of time, temperature, and burnup. This function was formulated as semi-empirical but, for specific conditions, was shown to be equivalent to a corresponding function derivable from a diffusion equation which accounts for trapping.

A comprehensive series of tests to measure temperature dependent failure of intact fuel particle coatings under core heatup conditions is ongoing. Irradiated coated particles are heated from 1100°C to temperatures as high as 2600°C at rates of 20, 50 or 185°C/hr. Fuel failure fractions are determined as a function of temperature from Kr85 release fractions. Tests have been conducted on TRISO UC_2 fissile fuel irradiated to 6 - 70% FIMA and TRISO ThO_2 fertile fuel irradiated to 2-8% FIMA. Results from tests on 886 TRISO UC_2 particles (Fig. 1) show that the fuel performance model used in AIPA is very conservative. The AIPA model assumed 100% coating failure at 2000°C; experimental data suggest an expected failure level of 3% at 2000°C and that 100% failure would not occur until temperatures exceed 2500°C. Although analysis is continuing, performance of TRISO ThO_2 fuel is similar to TRISO UC_2 fuel. The new data are being interpreted on the form of a more realistic semi-emperical model for total coating failure.

A combined analytical and experimental effort has been pursued regarding plateout behavior of fission products in the primary circuit. A first-version plateout computer program, called PADLOC, has been completed and documented (Ref. 4). This program solves mass transport and adsorption equations for a single nuclide species along defined multiple flow paths over defined surfaces. The solution considers a time-dependent radionuclide sources, radioactive decay, surface adsorption per given relationship, desorption, and surface heating by decay heat of plated-out fission products. Application of this version of the program to core heatup scenarios formed the basis for an updated AIPA assessment of iodine time-dependent release to the containment (Ref. 2).

The experimental program for iodine began with in-vacuum tests to provide data to the PADLOC code on iodine species formation and adsorption characteristics over core heatup conditions of surface temperature (130 to 830°C) and iodine vapor pressure (10^{-9} to 10^{-3} atm). These so-called static plateout tests showed that iodine undergoes rapid reaction with the Fe constituent of mild steel (such as in upper plenum elements or the PCRV thermal barrier cover plates) to form FeI_2. The rate of formation of FeI_2 was measured as a function of temperature and iodine partial pressure. It was observed that FeI_2 condenses along the adsorption tube surface over the 250 to 350°C temperature region. These tests showed that in general formation of FeI_2 must be considerated along with molecular iodine. Further, the resulting data provided the means for calculating the extent of plateout of FeI_2 at lower temperatures.

A second stage of testing under dynamic (flowing helium) conditions was conducted in FY-79 and FY-80 to provide verification and correlation data for the PADLOC program. Iodine transport was achieved by imposition of a low flowrate helium stream in a tube to simulate the convective flow conditions during core heatup. The I_2 was exposed to mild steel to form FeI_2 at high temperature and deposition characteristics of the produced FeI_2 were measured for fixed isothermal or temperature gradient conditions for comparison with PADLOC predictions.

Application of the FeI_2 reaction rate data from the static tests predicts fast and complete reaction of mild steel for the dynamic test conditions. This was confirmed by chemical analysis and iodine mass balance measurements. The peak concentration of condensed FeI_2 measured by means of gamma scanning occurred at temperatures around 200-400°C. This is in rough agreement with the PADLOC prediction, assuming all I_2 converts to FeI_2 and FeI_2 deposits along the tube according to its vapor pressure. The model correctly predicts the location of the plateout distribution peak. However, the data indicate movement of some of the adsorbed FeI_2 along the surface in the direction of lower temperatures, a phenomenon not simulated in the PADLOC model. Similar FeI_2 plateout profile data obtained from tests at Brookhaven National Laboratory (Ref. 5) were correlated with similar results (see Fig. 2).

The dynamic test series was completed at the end of FY-79 and in FY-80 an evaluation was performed of the test results. Present tests have provided adequate data on FeI_2 formation and deposition under simple laboratory conditions to enable PADLOC simulation of FeI_2 in future risk assessments. However, the following tasks are recommended for future work:

1. Completion of development of a multiple species version of PADLOC which can simulate chemical reactions, including reaction of the iodine with metallic surfaces (forming FeI_2, CrI_2, etc.) and possible reaction of iodine with metallic fission products in the fuel (such as cesium).

2. Laboratory measurements of the conditions under which chemical compounds other than FeI_2 can be formed and the rate of reaction as well as their plateout characteristics.

3. Heatup to failure of actual fuel particles and measurement of plateout characteristics of compounds formed.

While former tests provide input to the advanced PADLOC model the latter tests will provide data for code correlation and verification under integrated conditions which more closely simulate reactor conditions.

PCRV INTEGRITY

The PCRV integrity study was initiated to improve the accident simulation models that were used early in the AIPA study. It was recognized that the magnitude of radiological consequences predicted for core heatup sequences was dependent on assumptions that could not be fully verified with the simulation models then available. Since both the dominant risk and relatively highest consequence events predicted for the HTGR involve core heatup, and since this conclusion was arrived at on the basis of the quantification of a relatively small number of accident sequences, information obtained from the PCRV integrity study has been used to generate additional core heatup sequences resulting in potentially higher consequences than those predicted earlier. The updated risk assessment (Ref. 2) reflects the improved understanding of core heatup brought about by the PCRV integrity study.

The first part of the task was to model the entire primary system response, particularly through the coupling of the core cavity to the side cavities by natural convection and radiation. This is accomplished during pressurized heatup by implicit coupling of a RECA computer program (Ref. 6) model of the reactor core with a RATSAM computer program (Ref. 7) model of PCRV compartments and components. Once the reactor depressurizes, thermal radiation is the dominant means of heat transfer to regions outside the core. A model was then developed to assess side cavity heatup due to thermal radiation through the cross ducts. In this model, the core plenum surfaces radiate to the opening and walls of the duct. The heat then transfers by conduction through the metal thermal barrier cover plates and the kaowool material which insulates the PCRV liner and concrete.

At longer times during depressurized conditions, the CORCON computer program (Ref. 8) is used to simulate heat transfer out of the core, considering the fission product decay heat. An iterative procedure between the CORCON thermal analysis program and a fission product transport computer program, SORS (Ref. 9) was developed to track the fission product decay heat to determine realistic core temperatures and to accurately assess the decay heat released for subsequent critical component analysis. This procedure has realistically illustrated the large fraction of decay heat with migrates within and out of the HTGR core during the gradual attainment of high temperatures (Fig. 3).

The final aspect of this task relates to potential failure of PCRV tophead components and concrete degradation (Fig. 4). A version of the CORCON computer code has been developed to model tophead and sidewall failures while simultaneously calculating the heat transfer within the core and away from the core surfaces to the PCRV. The active heat transfer mechanisms are decay heat redistribution, conduction, and radiation. Thermal barrier, liner, and concrete failures are continuously monitored in the model. Component failure initially proceeds from the top head thermal barrier cover plate and kaowool insulation to the liner and PCRV concrete.

The component failure mechanisms that are simulated are the creep rupture and eventual melting of the thermal barrier and liner components, along with the spalling and melting of PCRV concrete. Concrete spalling is preceded by water boiloff and limestone aggregate decomposition into calcium oxide and carbon dioxide. A fraction of the liberated steam from the concrete will react with the hot graphite core upon contact.

The concrete degradation process represents a large thermal sink that impacts the core temperatures and the containment behavior. Recent work still in an early state has identified additional reaction energies and heat capacities previously not considered that will affect the ultimate termination of core heatup.

CONTAINMENT ATMOSPHERE RESPONSE

The containment structure is an effective barrier for holdup or retention of fission products released from the core and primary circuit. Hence, high priority was attached to assessment of fission product deposition in the containment along with analysis of potential modes of loss of leak-tightness, i.e., due to helium blowdown jet effects, flammability of combustible gases, or overpressurization due to gas accumulation.

In the first phase of the Containment Atmosphere Response (CAR) task, a computer program named CNTB (Ref. 10) was developed for analysis of transient containment pressure response to PCRV depressurization for various types of gas mixing, considering heat transfer to the building heat sinks. Use of this code demonstrated that the probability of containment overpressurization due to sudden helium depressurization through PCRV openings limited by flow restrictors is negligible irrespective of any mixing effects.

The second study phase (Ref. 11) focused on analytical models of depressurization jets and their effects on the containment structure. A computer program called JETWAY was developed for this purpose. Calculations using the computer program for a hot leg blowdown of PCRV helium discharging into helium accumulating at the bottom of the containment indicated that peak containment liner temperatures (i.e., the hot streak) from jet impingement do not exceed 150°C. The liner can withstand this temperature without significant probability of buckling. These jet models can also be employed to predict transient gas mixing and local gas concentrations in the containment when entrainment coefficients become available. These will be obtained from planned discharge tests investigating helium jets and gas mixing.

The third phase of the CAR task focused on the chemical response of the containment atmosphere during core heatup as documented in Refs. 12, 13. Event sequences leading to PCRV concrete degradation result in combustible and noncombustible gas species liberated to the containment at longer times (after several days). The CARCAS computer program (Ref. 13) was developed from the CNTB program to treat CO_2, steam, CO, and H_2 gaseous species in addition to helium added to the containment mixing. The program evaluates convective heat transfer to the containment surfaces, including effects of steam condensation. The potential for containment overpressurization is thereby determined.

For evaluation of potential flammability, the slow combustion and detonation limits of carbon monoxide and hydrogen in air were studied as a function of diluent fraction and temperature. Using a combined theoretical and experimental correlation approach, temperature and diulent dependent limits of flammability and detonation were derived and incorporated into the CARCAS computer program. At each time increment, the program tests the accumulated gas mixture in the containment against these limits to determine conditions under which combustion is possible, given an ignition source.

Analytical models were developed for a realistic determination of the pressure and temperature of the containment atmosphere during and after slow-combustion of carbon monoxide and hydrogen. Included are models for imperfect combustion and thermal radiation, heat convection, and steam condensation from the containment atmosphere to the boundaries during flame propagation. The results form the basis for evaluating possible impairment of the containment function by performing a structural response analysis.

Also, in the third phase of the CAR task, models were developed for fission product iodine adsorption on metallic and coated surfaces, adsorption and diffusion in concrete and interactions with condensing steam on containment boundaries and the cleanup filter system. These models were incorporated into the CARCAS computer program and applied to updated AIPA core heatup sequences in Ref. 2. Results indicate that at early times the surfaces readily adsorb iodine. Coated surfaces are as effective as the cleanup filter system in removing gas-borne iodine, whereas the concrete is relatively ineffective. After steam begins condensing, iodine in the coated surfaces is washed away and iodine in the untreated concrete is leached out to the containment drain and sump.

The description of the aerosol-like type activity (such as cesium, strontium, and tellurium) differs from the description of iodine vapor in the containment atmosphere. Development was initiated on models of aerosols within and leaking out of the containment. An analytical model was developed to account for gravitational settling in addition to filtration, to handle the aerosol removal by steam condensation. More elaborate models are, therefore, being considered.

RECRITICALITY EXAMINATION

An important safety research task is investigation of the AIPA risk assessment assumption that the reactor remains subcritical throughout a core heatup event with insertion of one or both shutdown systems for the long times associated with core heatup consequences. This is being pursued analytically and tests for model verification are planned. Time-and spatially dependent core temperatures were calculated using the CORCON computer program. Time-dependent fuel failure and transport of nuclides out of the core were calculated using a modified version of the SORS computer program. This program also computes slumping or compaction of the inserted control rods or B_4C reserve balls in their respective channels due to thermal and gravity effects. Vapor transport of the boron in the channel and diffusion of boron into the graphite surrounding the channel is simulated.

The above information was input to reactor physics computer programs to assess shutdown margins. MICROX, an integral transport theory flux spectrum program (Ref. 14), was used to generate cross-sections for the heavy metal, fission product, and moderator nuclides versus temperature. DTFX, an unpublished computer program using one-dimensional transport theory, was used to generate macroscopic cross-sections for various configurations of control rods, reserve shutdown system and boron diffused into the graphite. Calculation of the effective multiplication factor, k, for the core conditions at a specified time is performed by a two-dimensional multigroup diffusion theory code, BUG (Ref. 15), using the MICROX and DTFX cross-sections as input.

Two time points within the first two days were selected to consider the effect of control poison slumping and compaction. A later timepoint was selected to consider the second period of reactivity concern in which vapor transport at high temperatures may deplete a large volume of the central core of boron after many hours of heating. All three evaluations showed that the effective multiplication factor would be much less than 1.0.

However, since there are also large uncertainties in the transport of fission product poisons at the high core temperatures, preparations are in progress for experiments on boron carbide slumping behavior, vaporization, and diffusion in graphite. Included is a review of the phase behavior of the boron-carbon system and available vapor pressure data as well as diffusion coefficient data for boron in graphite. Mock-up (laboratory-scale) tests are proposed with the objective of validating the computer model used for predicting boron stability and transport.

CONCLUSIONS AND FUTURE PROGRAM DIRECTION

The safety research described above provides fundamental support to the HTGR probabilistic risk assessment (PRA) in the area of consequence assessments and has aided in confirming the low consequence magnitude due to the inherent safety features of the concept. The program is, therefore, important to the licensing of the HTGR particularly in view of the increasing emphasis on the use of PRA methods.

Future safety research priorities are being derived by applying value-impact methodology. A study has been performed which attempted to quantify potential reductions in risk uncertainties which candidate experimental or analytical tasks of closely defined cost and work scope could achieve. The benefit associated with each task was subjectively estimated as a percentage reduction in the uncertainty in consequence prediction at a mean frequency of 10^{-5}/reactor-year. For many research areas, the benefit was calculated using relatively sophisticated Monte Carlo uncertainty analysis methods as described in Ref. 16. Other areas could not be so quantified and their benefit values were subjectively estimated. Recommended future safety research areas resulting from this analysis include experimental assessment of PCRV component failure (e.g., thermal barrier failure, liner cooling system failure and concrete degradation characteristics), long-term iodine deposition within and release from plant barriers, and containment failure modes.

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REFERENCES

1. "HTGR Accident Initiation and Progression Analysis Status Report" ERDA Report GA-A13617, Vols. IV and VI, General Atomic Co., October 1975 to January 1976.

2. "HTGR Accident Initiation and Progression Analysis Status Report, Phase II Risk Assessment", DOE Report GA-A15000, General Atomic Co., April 1978.

3. B. F. Myers and R. E. Morrissey, "Licensing Topical Report: The Measurement and Modeling of Time-Dependent Fission Product Release from Failed HTGR Fuel Particles under Accident Conditions", DOE Report GA-A15439, General Atomic Co., April 1980.

4. W. W. Hudritsch and P. D. Smith, "PADLOC, a One-Dimensional Computer Program for Calculating Coolant and Plateout Fission Product Concentrations", DOE Report GA-A14401, General Atomic Co., November 1977.

5. "Reactor Safety Research Programs, Quarterly Progress Report, January 1 to March 31, 1978", NRC Report BNL-NUREG-50820, Brookhaven National Laboratory, April 1978.

6. J. F. Peterson, "RECA3: A Computer Code for Thermal Analysis of HTGR Emergency Cooling Transients", General Atomic Company Report GA-A14520 (GA-LTR-22), August 1977.

7. R. K. Deremer and T. Shih, "RATSAM: A Computer Program to Analyze the Transient Behavior of the HTGR Primary Coolant System During Accidents", General Atomic Report GA-A13705, May 1977.

8. K. E. Schwartztrauber and F. A. Silady, "CORCON: A Program for Analysis of HTGR Core Heatup Transients" General Atomic Report GA-A12868 (GA-LTR-13), July 1974.

9. M. H. Schwartz et al, "SORS: Computer Programs for Analyzing Fission Product Release from HTGR Cores During Transient Temperature Excursions", General Atomic Report GA-A12462 (GA-LTR-10) April 1974.

10. J. A. Landoni, "The CNTB Program for the Analysis of Partially Mixed Containment Atmospheres During Depressurization Events", ERDA Report GA-A13753, General Atomic Company, July 1979.

11. J. A. Landoni, J. V. Del Bene, R. K. Deremer, "Containment Atmosphere (CAR) Program Interim Summary Report" ERDA Report GA-A14262, General Atomic Co., May 1977.

12. J. A. Landoni, "Containment Atmosphere Response (CAR) Program Status Report", DOE Report GA-A14699, General Atomic Co., February 1978.

13. J. A. Landoni, "Containment Atmosphere Response (CAR) Program Second Status Report", DOE Report GA-A15582, March 1980.

14. P. Walti and P. Koch, "MICROX, A Two Region Flux Spectrum Code for the Efficient Calculation of Group Cross-Section", General Atomic Report GA-A10827, 1972.

15. J. P. Dorsey et al, "BUG-2/BUGTRI: Two Dimensional Multigroup Burnup Codes for Rectangular and Hexogonal Geometry" USAEC Report GA-8272, General Atomic Co., 1969.

16. D. J. Wakefield and A. W. Barsell, "Monte Carlo Method for Uncertainty Analysis of HTGR Accident Consequences", ANS International Meeting on Thermal Reactor Safety, April 8-11, 1980, Knoxville, Tenn. CONF-800403, Vol. II, pp. 736-743, 1980.

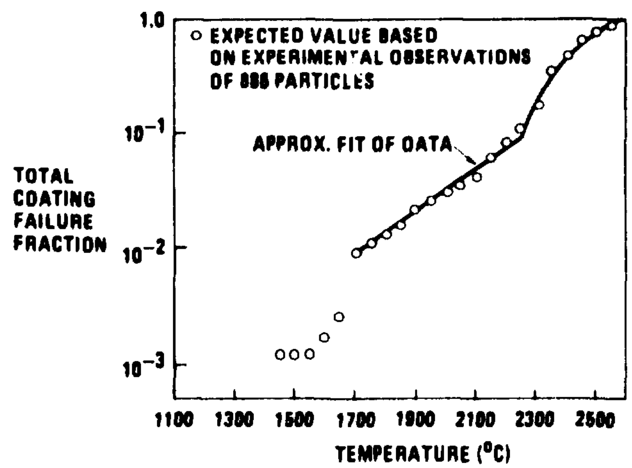

Fig. 1. Experimental data on particle coating failure temperatures for TRISO-UC_2 particles during core heatup conditions

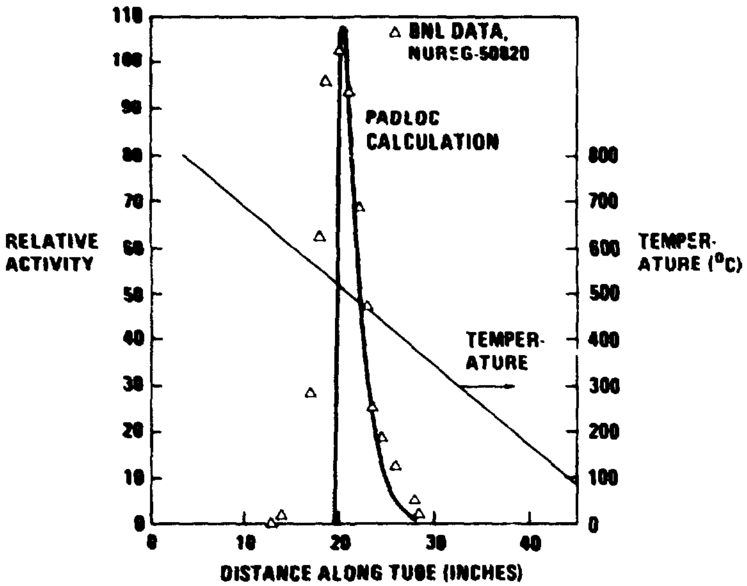

Fig. 2. Correlation of FeI_2 plateout profile

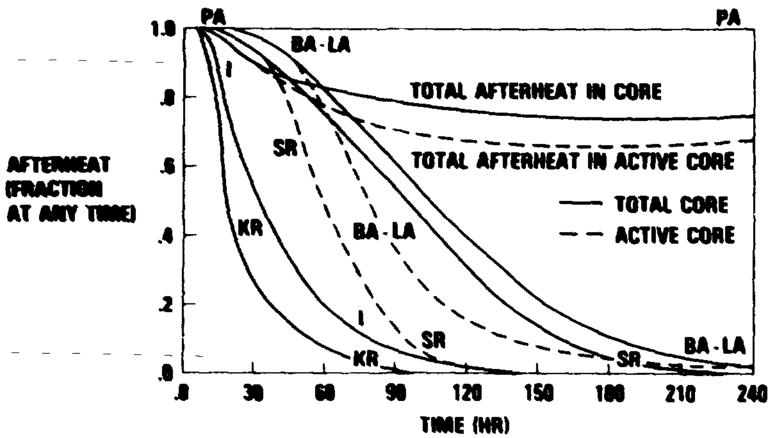

Fig. 3. Fraction of afterheat remaining in core during heatup

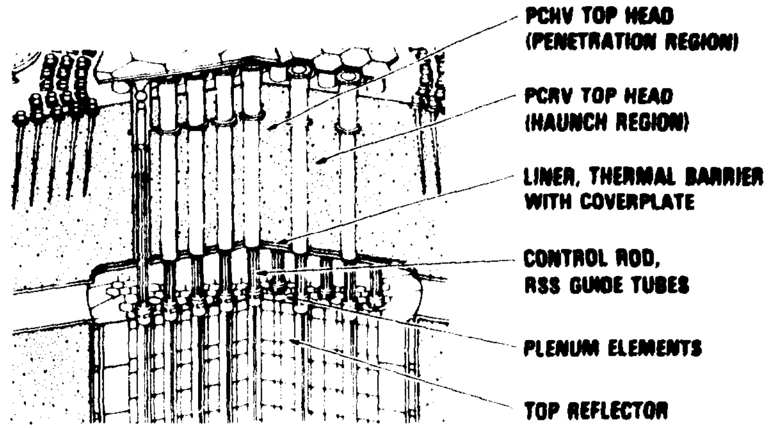

Fig. 4. Upper core cavity arrangement