RULES FOR DESIGN OF NUCLEAR GRAPHITE CORE COMPONENTS SOME CONSIDERATIONS AND APPROACHES

V. SVALBONAS, T. C. STILWELL, Z. ZUDANS
Engineering Department, The Franklin Institute Research Laboratories,
The Benjamin Franklin Parkway, Philadelphia, Pennsylvania 19103, U.S.A.

SUMMARY

The use of graphite as a structural element presents unusual problems both for the designer and stress analyst. When the structure happens to be a nuclear reactor core, these problems are significantly magnified both by the environment and the attendant safety requirements. In the High Temperature Gas Reactor (HTGR) core a large number of elements are constructed of nuclear graphite. This paper discusses the attendant difficulties, and presents some approaches, for ASME code safety-consistent design and analysis. The statistical scatter of material properties, which complicates even the definitions of allowable stress, as well as the brittle, anisotropic, inhomogeneous nature of the graphite was considered. The study of this subject was undertaken under contract to the U.S. Nuclear Regulatory Commission.

In the course of the study the following topics were among those broadly investigated, and recommendations for each are presented.

(1) It was found that analytic statistical methods used to arrive at a definition of minimum ultimate strength, without considering actual experimental acceptance testing procedures for the graphite material, were totally unrealistic, often providing negative values of the allowable stresses. A procedure is outlined which incorporates the truncation effects on the probability distribution function due to material acceptance tests, and utilizes such testing concepts to simply produce a value of minimum ultimate strength.
(2) It was concluded on the basis of presently available evidence that the distinctions between secondary and primary stresses are inappropriate to graphite structures. Various arguments for promoting such a distinction are reviewed and countered.
(3) The proposed overall design criteria and stress limits for graphite structures were reviewed. It is concluded that, while much of the design basis was drawn from the ASME design criteria for metal structures, a literal adoption of numerical safety factors may not lead to equivalent safety for materials like graphite. An attempt to obtain a new set of safety-consistent numerical factors is presented.
(4) The use of the homologous stress concept in graphite fatigue calculations was reviewed. It was concluded that such calculations become very sensitive to exact knowledge of a minimum ultimate strength, and thus prone to substantial errors unless material descriptions are standardized by use of tests.
(5) The overall design philosophy for brittle materials is applied to HTGR core structure design including such areas as:
  - graphite oxidation,
  - component proof tests,
  - experimental seismic modeling,
  - fracture analysis.

The use of such a brittle materials design philosophy resulted in a number of recommended procedural modifications in these areas to better obtain a safe-life HTGR core structural design.

1. Introduction

In steam cycle high temperature gas reactor (HTGR) technology there is substantial use of nuclear graphite as a structural material in the core components. This is demonstrated both in potential "lead plant" designs and in the existing Fort St. Vrain plant. Typical graphite core components include fuel elements, replaceable and permanent reflector elements, core support blocks, posts and post seats. Some potential configurations of these components are provided in Figs. 1 and 2.

There are numerous problems associated with introducing a material such as nuclear graphite as a structural material for reactor core components. The types of problems encountered are amenable to classification into three basic groups:

(i) materials related - This category would include all problems relating to property definitions under HTGR environmental conditions. The properties to be considered include oxidation characteristics, irradiation induced dimensional changes and creep, and variation of properties and strength with HTGR environmental factors and age. The difficulties in this category compound the problems of a stress analyst by not providing an easily useable materials model for reserve strength predictions.

(ii) analysis related - The biggest problem in this category is only partly related to graphite. This is the problem of seismic analysis of a structure with the interconnectivity characteristics (mainly dowels) of the HTGR core. Besides the extreme difficulty involved in analytic characterization of such a three-dimensional structure, the nuclear graphite must be used to obtain all relevant coefficients for impact and energy absorption or transfer. The difficulties inherent in the pure analytic approach lead naturally to experimental analyses, and in turn, to the difficulties associated with a statistically described material in areas such as scaling, and experiment-analysis correlation.

(iii) design criteria related - For light water cooled reactors, stress limits for core support structure and certain of the core internals are provided by Subsection NG of Section III of the ASME Boiler and Pressure Vessel Code. But there is, as yet, no similar pre-established, authoritative and sanctioned set of design rules to provide guidance for design of corresponding components when they are to be constructed from graphite. Section III, Division 2 design philosophy is based on concrete always being reinforced with steel, and thus does not realistically apply to design of quasi-brittle, statistically described materials. The designers of the HTGR therefore must themselves propose a set of analytical procedures and design rules, together with stress and deformation limits whose purpose is to assure the structural integrity of these graphite components in conformance with the safety oriented spirit of the ASME codes.

Some potential solutions and approaches to be used in overcoming the above classified problems form the basis for the present paper.

2. Design Criteria

There are many bases which can be used to establish a particular design criteria. In the present context of graphite reactor core components, the application of a base criteria which would provide assurance of structural integrity equivalent to that already established for light water cooled reactors by Section III of the ASME Code (Subsection NG) is especially attractive.

The implementation of such a general philosophy will establish an approach for the selection of design limits which is both rational and objective. It will set up a basis from which stress limits can be assigned numerical values consistent with good design practice and with standards that have gained general acceptance throughout the industry as appropriate to nuclear power plant component design. It will likewise tend to free these limits from individual engineering judgements of what may be necessary or adequate, and provide a frame of reference for objective discussion and evaluation of proposed limits. Finally it will allow the analyst familiar with present nuclear code procedures to maintain:

- a similar categorization of stresses,
- many paralled procedures for analysis and evaluation,
- direct carry over of the numerical safety factor concept, and cross referencing to the present Section III provisions.

2.1 Minimum Ultimate Tensile Strength

For metallic structures the ultimate strength is easily definable, while for nuclear graphites the statistical nature of quasi-brittle strength must be considered. In this regard we have available one simplifying procedure, i.e., rejection of low strength samples through a well constructed materials acceptance test program.

Normally, for brittle material design, the tail of the probability of failure versus stress curve is the region of interest for setting allowable failure probabilities. It is just this region which is defined by only a few out of hundreds of test points, and thus *any* mathematical distribution function can reasonably be postulated, apriori, to be valid in this region. Since the most important region is so hard to accurately establish experimentally, it becomes somewhat irrelevant, for the present purposes, how well a particular distribution function may fit the data in other areas.

A number of distribution functions can be adjusted to fit mid-range data almost equally well. If these are intelligently selected, all will also possess low probability tails. But it is precisely in the tails that the differences among the assumed distribution functions arise. Although in the tails the numerical values of the probabilities are small, the ratio between tail values (as given by one distribution function or another) may be large. Since the tail values govern the safety of design, the inferences that may be drawn based on one assumed distriburion function will be sufficiently different from those resulting from an alternate choice. Since experimental data in the tail region is very sparce, it is hard to verify which distribution function accurately represents the data and which does not. Consequently, basing design allowables upon probabilities obtained by extrapolating mid-range data to the tail is a risky procedure.

For the above reaons there exists little rationale for setting allowables on the basis of assumed mathematical distribution functions. What should be sought instead is a procedure to better define, or obtain, the tail of the experimental probability of failure curve. The use of a materials acceptance test to truncate the experimental probability curve can be used for this purpose. Such an acceptance test may be made at a stress level which provides an economically acceptable material rejection rate.

The effects of using such a test are provided by Dally and Hjelm [1]. The results prove that the long tail on the probability of failure curve for the virgin material can be mostly eliminated by proof-testing. The improvement of this material (CFW graphite) from a design viewpoint is remarkable. With the virgin material a beam designed at a stress level of about 300 psi would exhibit a 1% probability of failure. With the proof-tested material, however, the stress level could be increased to about 2,000 psi with the same risk of failure. This improvement is obtained at the cost of a 15% rejection rate. Thus any design procedure without the use of a material acceptance test appears unrealistic.

In nuclear grade graphite a special testing procedure must be recommended since the strength of a graphite log itself may vary from location to location within the log. First, the weakest point in a log must be located experimentally. Although this point may be expected to be at the very central-most region, this should be checked by a series of tests for each fabrication procedure. These tests require taking an initial series of logs and cutting from them a large number of specimens, each representing a geometric location within the log. From these specimens a strength distribution curve may be obtained for each log, and thence from sampling procedures on all the logs, a confidence level can be established that the weakest region (to a suitable level, i.e., 95 or higher) has been identified. Since the weakest region for the fabrication process is thus established, each log delivered for manufacturing HTGR components is tested on a sample from that weakest region, to a prescribed acceptance test stress level. Failure to meet the acceptance test disqualifies the total log. Similarly the allowable ultimate strength can now be set to some "statistical assurance factor" (<1) times the material acceptance test stress. The use of this factor considers the slight uncertainty that indeed the worst part of the graphite log was tested, and may also be used to cover small strength distribution changes due to minor adjustments in the fabrication process. That these changes are indeed small should be properly verified [2,3].

There may exist some possibility that the weakest section, as defined by earlier material tests, cannot be tested in the log delivered for component fabrication. In this case a weakest section of those available for testing should be chosen and acceptance-tested. The acceptance-test value for this specific log shall then be taken as a correspondingly higher value to reflect that the truly weakest point in the log was not tested. The earlier described material tests are thus required to be detailed enough not only to locate the weakest point in the graphite log, but also to provide a description of expected strength versus location in the log. They may also be used to obtain an expected failure surface for the graphite material.

2.2 Stress Categories and Factors of Safety

Once a proper procedure for obtaining the minimum ultimate strength, S_u, is established, one may consider assigning stress limits to the several stress categories and loading conditions. An important consideration in establishing stress limits is the failure criteria to be used to test stresses in the structure against the limits.

The failure surface of graphites has been studied both experimentally and theoretically [4]. Several theories have been proposed to describe the failure mechanism. The most successful of these produce failure boundaries which fit the experimental data fairly well. But all must be regarded, at this stage of the knowledge, as hypotheses. Practical graphite structures must meanwhile be designed. Since experimental descriptions of the failure surface are available (or can be established for particular cases of interest), design may safely proceed in the absence of an established theory. However, to assure safety in the absence of an established failure theory, the design should be sufficiently conservative so that stresses are kept remote from all of the postulated surfaces and the experimental data as well.

The analyst requires a tool to help him limit stresses to acceptable values. Any reasonable representation of the failure surface will furnish such a tool, provided the factors of safety used in conjunction with this particular failure surface are sufficiently higher to always keep stresses within safe limits as defined by other, more accurate, formulations of the failure criteria. Under such circumstances, a simple tool is preferable to a complex one. Thus a maximum stress theory, properly modified for material anisotropy and shear strength considerations, and used with proper stress limits, may be even preferable to one which is more exact but considerably more complex [4]. This is especially true when one considers that the variation of the failure surface with HTGR environmental conditions must be known.

2.2.1 Stress Limits

For metals the ASME Code Section III establishes three major categories into which stresses within a structure may be classified. Generally, these stress categories are distinguished by:

- the type of loading which gives rise to the stress,
- the effect that the stress has on design safety.

Typically, stresses assigned to a particular category result from the same types of loadings and give rise to the same types of structural effects. Because the effects of the stresses in each category are different, different stress limits are specified.

The categories as defined by the ASME Code are given below. *It is important to note that these are defined for ductile materials, and to observe the way that the effects of ductility influence the definition of each category.*

- Primary stress is any normal stress or a shear stress developed by an imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses which considerably exceed the yield strength will result in failure or, at least, in gross distortion. A thermal stress is not classified as a primary stress. Primary-membrane stress is divided into general and local categories. A general primary-membrane stress is one which is so distributed in the structure that no redistribution of load occurs as a result of yielding.
- Secondary stress is a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can staisfy the conditions which cause the stress to occur and failure from one application of the stress is not be expected.
- Peak stress is that increment of stress which is additive to the primary-plus-secondary stresses by reason of local discontinuities or local thermal stress (see NB-3213.13(b)) including the effects (if any) of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture. A stress which is not highly localized falls into this category if it is of a type which cannot cause noticeable distortion.

In drawing comparisons between different design bases, one must be careful not to think of factors of safety as independent entities which may be considered and compared in isolation from other provisions of the code. Instead one must regard the code as an integral package in which the safety factor is related to, and dependent upon, fulfillment of other design provisions.

The ASME Code, Section III, Nuclear Components, specifically provides:

- A list of permitted materials.
- Tables of material strengths and properties known to be conservative for design use.
- Materials test requirements and acceptance standards.
- Quality assurance procedures.
- Acceptable and unacceptable design configurations.
- Pre-service pressure test and in-service inspection requirements.

In addition the code (either implicitly or explicitly) counts on:

- The margins of reserve strength inherent in ductile and strain hardening materials.
- Past experience with comparable structures in service.
- Modern methods of analysis with verified computer structural analysis programs.

All of the elements listed above are related to, and influence, the selection of factors of safety [5].

In establishing a stress limit for graphites to protect the fundamental load carrying capability, one must take into account that the design provisions and basic assumptions associated with the design rules for metals in the ASME Code *cannot be rigorously duplicated for graphites*. It is clear that the unique characteristics of graphites and the present state of the art for design with graphite materials do not permit stress prediction to the same degree of certainty as can be provided for metallic designs.

In fact, stress analysis of graphite structures will usually provide only the most probable values of stresses, strains and deflections, because the values of the physical properties, upon which stress computations are based, have a statistical spread. This is in contrast to the near actual values expected from similar computations for metal structures.

In this respect there will be an important distinction in the quality of analytical results based on the type of structure being considered. If the structure is *statically determinate*, stresses from applied external loadings will be nearly exact. Corresponding deflections, however, may not be similarly accurate. If the structure is *redundant*, stress results will necessarily be statistical in character.

Consequently, if one were to stipulate safety factors for graphites equal to those for metals, equivalent safety would not be achieved. Equal protection will require a higher safety factor for graphites.

2.2.2 Stress Categories

The three standard stress categories used in metals nuclear design were defined earlier. In metals the effect is different for each stress category and the reason for these differences is directly attributable to metal ductility. For secondary stresses (self-equilibrating stress systems), ductility provides the mechanism to enable stress relief. For peak stresses, ductility permits high local strains to be accommodated without appreciable effect on nearby structures.

Graphites, lacking the ductility of metals, should not be expected to respond to the three stress categories as metals do. While cracking can be postulated as a mechanism for secondary stress relief, it cannot be always be relied upon to be self-contained nor uniformly applicable under all circumstances [6]. Thus, in graphites, secondary stresses cannot be counted upon to always produce effects significantly different from those of primary loads. Since primary and secondary stresses appear to have equal potential to impair the ability of graphite to carry basic mechanical loads, they should not be assigned unequal stress limits. Primary and secondary stresses should constitute a single stress category for graphite, to which a single stress limit should be applied.

In fact, treating primary-plus-secondary stresses as a single stress category has, in the past, been conventional practice for brittle materials. To require similar treatment in graphites is merely to state that graphites have no demonstrable special characteristics so distinct from other brittle materials that conventional practice may be safety abrogated.

Since the category of primary-plus-secondary stress is the basic stress category upon which continued load carrying capacity depends, the basic factor of safety applies. The applied factor should be maintained on the minimum ultimate tensile strength as determined by the procedures defined earlier.

While, for brittle materials, the distinction between primary and secondary stress based on their consequence to structural integrity may fade away, in contrast, the peak stress category appears to retain much the same significance in brittle design as it held for ductile design, and its impact on structural integrity is broadly similar in both types of materials.

In ductile materials local yielding develops in regions of peak stress to accommodate the local strain pattern. Brittle materials appear to behave in much the same way except that the local strain pattern is accommodated by the development of a *locally restricted* crack system. For example, in [7] concrete slabs containing circular and diamond-shaped holes were loaded to generate the classical patterns of stress (strain) concentration associated with such holes. The region of strain concentration was studied to observe the brittle material response. At the edge of the hole very large strains indicative of local cracking were observed; but no discernible increase in stress or strain was evident in regions remote from the holes.

This behavior seems characteristic of those brittle materials which do not shatter readily and can be given an heuristic explanation. Peak stresses arise in, and are confined to, local regions. Although the peak stresses themselves may be high, the area over which they act is small, consequently the total force with which they are associated is low. Thus even if the peak stress area cracks, transferring force to neighboring regions, the ensuing stress increment is small. Moreover, the cracking pattern that develops appears to accommodate itself to the strain pattern in such a way as to relieve strain concentration. Thus it does not become self propagating if the initial steady load is maintained. Tests involving such peak stress states at the surface, produced by thermal shock, have been documented by Stenger [8] and appear to justify the use of a different safety factor.

2.2.3 Special Stress Limits

Section III of the ASME Code recognizes the principle that all components are not equally vital to the safety of a reactor and that consequently design requirements may differ from component to component, in accordance with their importance to reactor safety. This recognition is indirect. Section III of the ASME Code establishes three classes of design requirements -- Class 1, Class 2 and Class 3. These correspond to levels of structural integrity and quality of manufacture, Class 1 requirements being the most stringent.

The nuclear power plant components code does not attempt to give guidance as to assignment of individual components to the three quality classes. It states that guidance for selection is to be derived from system safety criteria applicable to specific types of nuclear power systems. The American Nuclear Society provides published criteria for safety classes which may be used to assign components to appropriate ASME Section III quality classes.

Both the ANS and the ASME criteria classify structures at the major component level. Neither attempts to assign safety classes or quality classes to individual parts or subassemblies within a major component. Thus, under Section III of the ASME Code, the same general set of stress and deflection limits apply to all parts within a given component.

However, in establishing design rules for graphite structures, it does not seem mandatory that this precedent be rigorously followed. Specifically there appears to be no compelling reason that a special stress limit could not be established, for combined thermal, irradiation and mechanical stress in fuel block webs *provided that it can be rigorously demonstrated that safety is not impaired as a result of the chosen stress limit.*

It is believed that it may be justifiable and also necessary to allow a more liberal limit on stresses in fuel block webs than is permitted elsewhere in the core structure.

If this is done, it is best, as a matter of procedure, to grant a specific exemption from a more rigid general rule rather than to relax the general limit to accommodate a special circumstance. A specific exemption will require specific justification both for the original case and also for future extension to other applications.

Some or all of the following factors possibly may provide a basis for justification of higher stress limits in fuel block webs. The impact of each factor on structural integrity should be evaluated.

- Fuel blocks have a relatively short residency in core.
- The major stresses may be thermal and consequently cannot develop unless graphite temperature is high. Credit for higher graphite strengths at these temperatures might be allowed.
- The most severe stress results from a once occurring load. This condition may be identified as the stress occurring in the web between adjacent fuel holes during the shut-down after approximately one year's residency.
- It may be possible to demonstrate that web cracking may not impair function or increase safety hazards. This point must be carefully documented. Interest centers on the most severely cracked block (from population of over 300 blocks) *not on the most typical block.* Effects of repeated (but lesser) loadings after initial web cracking should be considered. Assurance that chips or wear particles will not block coolant passages should be provided.

3. Experimental-Analytical Correlation

Both safety requirements and seismic analysis correlations and justifications may be demonstrated by testing. The use and extrapolation of proof tests must, however, demonstrate proper cognizance of the statistical nature of the graphite material. The only safety factor to be considered of use is the safety factor that may be applied at end-of-life for a component. To infer the value of this safety factor from a single satisfactory test (wherein the materials can only be taken as representative of the 50% curve) on virgin specimens is totally erroneous. Such would not be a true safety factor due to the material statistics, even if the test could be comprised to consider all the effects as:

- oxidation
- fatigue
- irradiation and long term creep
- thermal effects including "hot streaks"

Similarly, extrapolation for seismic g magnification from the test would not be possible. The tests can only have true effectiveness when carried to destruction, and when the *exact* strength properties of each component specimen graphite are known. The true strength properties must then be used in a realistic three-dimensional analysis to correlate the experimental findings. By using accurate analytical procedures the expected results can also then be *extrapolated to predict the component failure strength for the weakest acceptable graphites.* The tests should also be configured so as to directly consider as many of the listed effects as possible experimentally, with the others being included in later analytical calculations.

Such stringent requirements for test-analysis correlation and extrapolation to weakest acceptable specimens may possibly require nonlinear analysis procedures if the mathematical materials models show such nonlinear behavior exists prior to sample destruction. The meeting of such requirements would be almost impossible in HTGR core seismic analyses. Thus the use of biased experimental models may be recommended. Such models would contain simulation of items such as failed dowel pins or cracked webs in fuel blocks if the combined statistics of the material and load descriptions indicated a potential probability of such item existence prior to initiation of a seismic event.

4. Material Properties

In examining the problems associated with creating conservative mathematical materials models for use in stress analysis of nuclear graphite structures one is struck with the number of potential variables that exist (irradiation, temperature, porosity, oxidation) as well as by the problem of statistical variation in most mechanical properties (Young's Modulus, Poisson's ratio, thermal conductivity and expansion coefficient). While we are familiar with dealing with temperature-dependent properties for metals, the associated statistical variation of properties in graphites may tempt one to require that parametric studies be carried out at various stages of stress analysis to be sure that conservative answers are being obtained.

Since the above is extremely difficult, if not impossible, for complex structures, and most likely will not yield results with proven conservativeness, it may rather be postulated that the variation of material properties and strength can be explained using the *same basic theory,* i.e., the elusive micromechanics model for graphite. This verbal or pictorial model is utilized to explain strength variations on the basis of different granular strengths, joining of micro-cracks, and progressive fracture. The *same model* is equally applicable for explaining statistical scatter in Youngs' Modulus when one considers that a strain or deformation gage is actually measuring overall macro-phenomena for graphite. Since the flaws are statistically distributed from sample to sample it is equally plausible to postulate that their growth and joining can result in different elongation measurements from sample to sample. Similarly, variations in flaw distribution and growth with temperature can also be postulated to explain the scatter of measured coefficients of thermal expansion or heat transfer. The stiffer characteristics of the bend test specimen [9] can thence be explained by stating that not all the grains around voids are equally stressed (as in pure tension), and since microcracking makes less progress this is, in turn, reflected in a smaller overall deflection measurement.

The above reasoning allows us, once again, to tie all statistical behavior to a single source, i.e., the *statistical distribution of local flaws*. This argument can now be reversed in the following manner:

(i) First consider that the HTGR components are limited to a working stress based on very low probabilities of failure;

(ii) Consider also that material testing has eliminated weak logs or specimens, i.e., the tail of the fracture probability curve has been truncated;

(iii) Therefore, since property variability can be tied to flaw distribution, and since this distribution is truncated by a testing procedure (ii) *and* by specifying a correspondingly low operating stress range (i), it may be postulated that the material properties will exhibit *much less statistical variation under these restrictions than may be exhibited by a full population of random virgin test samples in a laboratory.*

On the basis of the above argument it seems unnecessary to consider the full possible range of material property variability in a given analysis of a macromechanical type. Indeed the variability considerations should be restricted to conditions which *mirror the stress restrictions*. This in turn would lead one to suppose that the range for the stress-strain law due to the statistics of material property variation above, would not be too wide, and a conservative, even linear, curve could be properly chosen for use in stress analysis.

5. Research Requirements

While the above discussions may serve to provide some logical basis upon which to organize graphite analysis and design procedures, much of what has been noted remains speculation and needs further verification in research and testing. Topics which may need substantial further efforts can be listed as:

(i) oxidation-strength models for graphite

(ii) seismic testing and analysis correlations

(iii) fatigue behavior, and descriptions by fracture mechanics procedures

(iv) further correlative experiments involving stress categories and associated limits and failure criteria.

References

[1] J. Dally and L. Hjelm, "Proof-Testing Graphite and Its Design Implications," Jr. of the Amer. Ceramic Soc., Vol. 48, No. 7, (1965).

[2] R. J. Price, "Statistical Study of the Strength of Near-Isotropic Graphite," GA Report No. GA-A13955 (1976).

[3] P. Williams, Summary of Meeting Held on February 16-17, 1977 to Discuss Graphite Design, NRC Docket 50-538, March 8, 1977.

[4] T. Y. Chang and T. Weng, "A Strength Criterion for Graphite Under Combined Stresses," paper presented ASME PVP Meeting (1975).

[5] ASME, Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Section III and VIII, Division 2, The Amer. Soc. of Mech. Engrs., (1969).

[6] V. Svalbonas, T.C. Stilwell, Z. Zudans, "Evaluation of the Structural Integrity of High Temperature Gas-Cooled Reactor (HTGR) Core and Support Elements," FIRL Report No. F-C4230 (1976).

[7] I. Imbert, "The Effects of Holes on Tensile Deformations in Plain Concrete," Highway Research Record No. 324 (1970).

[8] D. Stenger, "Failure Stresses Due to a Thermal Gradient in Near Isotropic Graphite," GA Report GA-A13872 (1976).

[9] J. Broklehurst and M. Darby, "Concerning the Fracture of Graphite Under Different Test Conditions," Matls. Sci. and Engrg., Vol. 16 (1974).

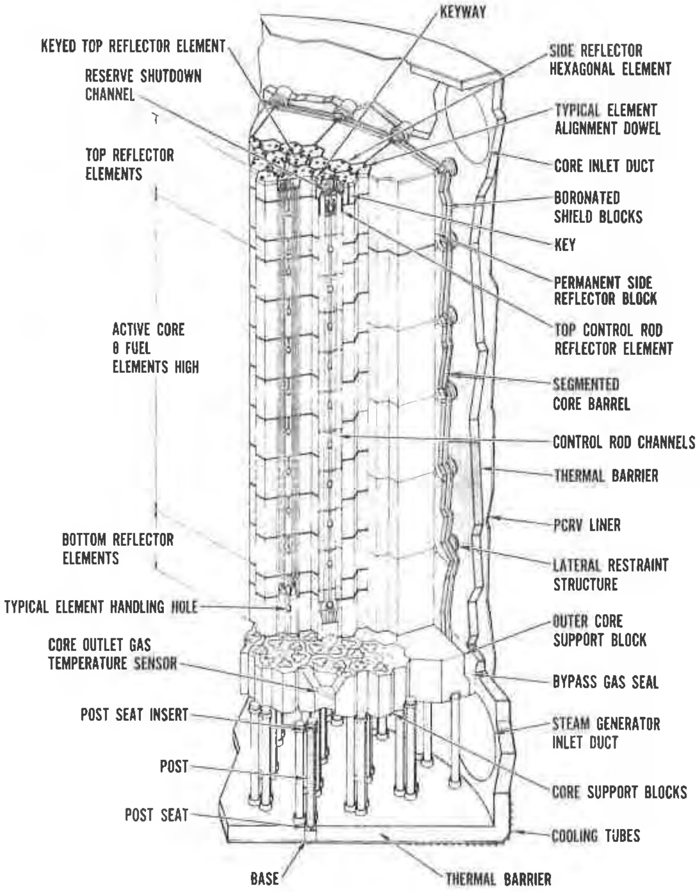

Figure 1. Reactor Core Arrangement (GASSAR-6)

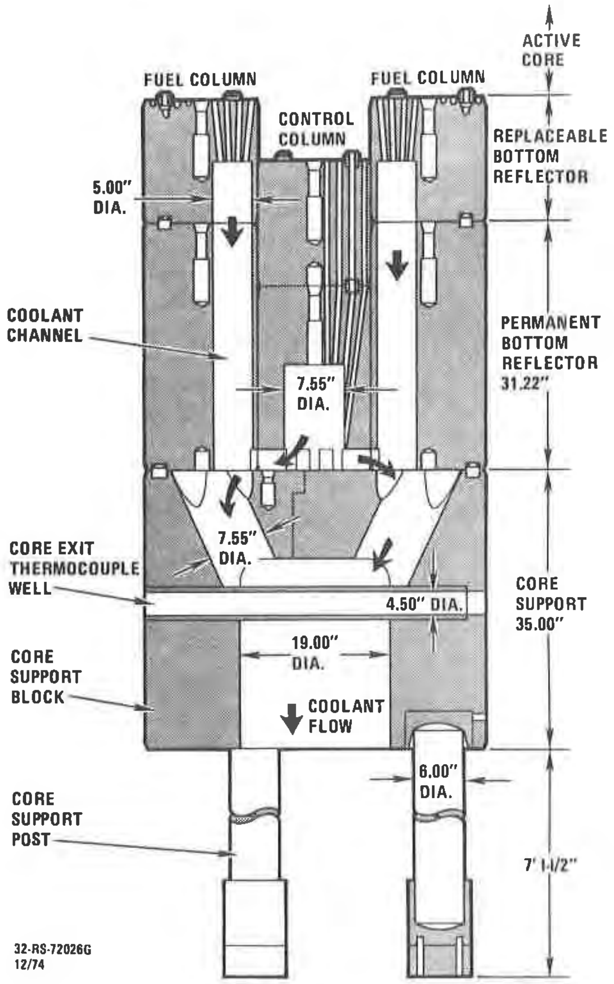

Figure 2. Bottom Reflector and Core Support Details (GASSAR-6)