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T. D. Dunn, A. A. Schwartz and F. A. Silady

ABSTRACT

In 1990 a cost reduction study recommended that the reference U.S. MHTGR module design be changed to an 84-column, 450 MW(t) annular reactor core to attain improved economics with the same high level of safety as the previous reference 66-column, 350 MW(t) MHTGR module. The objective of this paper is to report on a recently completed core configuration trade study that reviewed the basis for that recommendation with more detailed assessments. The trade study examined alternate core configurations in terms of the size, shape, and power level. Core configurations at 450 MW(t), an alternative at higher power, and one at lower power were considered. These alternatives represented the maximum achievable power for fuel element for two different reactor vessel sizes. Fuel, reactor internal and vessel temperatures during pressurized and depressurized conduction cooldown transients are presented and compared to limits. Based on the need to improve economics without sacrificing the MHTGR's high level of safety, the trade study confirmed that the previously selected 84-column, 450 MW(t) annular design remains the preferable configuration.

INTRODUCTION

In October of 1990 the Cost Reduction Study (CRS) (Ref. 1) recommended that the reference MHTGR design be changed to the 84-column, 450 MW(t) annular reactor core design. That recommendation was based on the objective of attaining improved MHTGR economics in a reactor module that offered the same high level of safety as the 66-column, 350 MW(t) MHTGR described in the Preliminary Safety Information Document submitted to the U.S. Nuclear Regulatory Commission. The 84-column, 450 MW(t) design appeared to best meet the utility industry objectives. Since that time, more detailed assessments have been performed on the 450 MW(t) design.

The objective of the core configuration trade study was to review the CRS recommendation with knowledge of the more detailed assessments that have been performed. The study more thoroughly examined alternate core configurations, in terms of size, shape, and power level, to best satisfy the utility needs. The scope included the 84-column, 450 MW(t) core, other core configurations at 450 MW(t), and alternatives at higher and lower powers than 450 MW(t), corresponding to the maximum achievable for two different reactor vessel sizes. The trade study was structured to provide visibility to the strengths and weaknesses of each alternative relative to the top level requirements.

KEY REQUIREMENTS AND STUDY CONSTRAINTS

Top level user and regulatory requirements are given in the US-DOE MHTGR program's Overall Plant Design Specification (OPDS). An alternative core configuration was considered viable only if it satisfies these mandatory requirements or **musts** of the plant. However, since the margins by which an alternative meets the top level requirements vary, the requirements also served to define desirable, rather than mandatory, objectives or **wants**.

The mandatory requirements or **musts** define the desired results and the limitations for the core configuration trade study. As discussed in the Cost Reduction Study the plant costs of any alternative plant must be competitive with coal plants. Two key safety requirements for the MHTGR plant are judged essential to commercial deployment:

1. The plant shall be designed to perform its safety functions without credit for sheltering or evacuation of the public beyond the plant's exclusion area boundary.

2. The plant shall be designed to perform its safety functions without reliance on control room equipment, the automated plant control system, or operator actions.

In order to meet these **must** requirements, acceptable response needed to be demonstrated for pressurized and depressurized conduction cooldowns. These are rare events in which the diverse active coding systems are unavailable and heat removal is by passive means to a heat sink exterior to the uninsulated reactor vessel. Alternatives must also possess adequate shutdown margin, reactivity control and fuel performance which tend to limit the allowable average core power density. The core height was restricted to 10 or fewer fuel blocks to assure both seismic and nuclear axial stability, while factory offsite manufacturing and shipping limitations control the reactor vessel and steam generator maximum weights and sizes. To assure that there will be no degradation in the level of safety, constraints to increasing power output and to more cost effective design selections imposed by the reactor core and internals, the steam generator, circulator and fuel handling and storage were taken to be the same as in the CRS. Table 1 lists all the **musts** used for selecting the core configuration alternatives of this trade study.

TABLE 1
CORE CONFIGURATION SELECTION CRITERIA MUSTS

Normal Operation/Refueling

- Provide shutdown margin of 1%
- Provide effective reactivity control
- Provide axial power stability
- Meet reactor vessel/steam generator vessel shipping weights/sizes
- Meet fuel performance limits
- Mean busbar costs < $2000/kWe

Offnormal

- Meet depressurized conduction cooldown (DCC) and pressurized conduction cooldown (PCC) temperature limits
- Meet protective action guidelines limits

The selection criteria that provide the desirable objectives or **wants** for the core configuration study are given in Table 2 in order of descending importance for both normal and off-normal operation. Only **wants** which discriminate between alternatives were included. The selection criteria fall naturally into categories that improve the design in the areas of plant economics, passive safety or design margins. High priority was given to capital and operating cost reduction. Furthermore, maximizing the development cost benefits of commonality with the MHTGR-New Production Reactor (NPR) was assigned a moderate priority. At this stage of the design, in order to meet the passive safety requirements, margin in fuel and component temperature limits during conduction cooldowns were required. Other design area margins were assigned lower relative importance. By assessing the overall plant economics, passive safety and design margins, the best core configuration was selected.

TABLE 2
CORE CONFIGURATION SELECTION CRITERIA AND THEIR IMPORTANCE

Selection Criteria (Wants)		Relative Importance
Normal Operation		
1.	Provide cost margin relative to coal	High
2.	Utilize development cost benefit of NPR	Moderate
3.	Provide margin on peak fuel temperatures	Low
4.	Provide margin on vessel fast fluence limits	Low
5.	Provide margin on core pressure drop limits	Low
6.	Provide component design margin	Low
Off-normal Operation		
1.	Provide margin on PCC temperatures	Moderate
2.	Provide margin on DCC fuel temperatures	Moderate
3.	Provide shutdown margin during cold water ingress	Low
4.	Provide margins for unprotected reactivity events	Low
5.	Provide seismic margins	Low

ALTERNATIVE CORE CONFIGURATIONS

The purpose of this core configuration study was to examine alternative core designs which satisfy both safety and economic requirements. Therefore, the alternative designs which were considered encompassed the maximum power level [410 MW(t)] that can safely be attained within the smaller vessel that was used in the 350 MW(t) design (the NPR design), as well as the maximum power level [500 MW(t)] that can be attained within the larger vessel used in the 450 MW(t) design. Cores with lower power levels were not considered because they were found in the Cost Reduction Study to not be economically viable. Cores with higher power levels were not considered because of either conduction cooldown temperature constraints or because they would require onsite vessel fabrication.

Five alternative core designs as illustrated in Fig. 1, which met the must requirements were evaluated. These are as follows:

A. The reference 84-column, 10-layer, 450 MW(t) core, which was the recommended design in the MHTGR Cost Reduction Study. This core design utilizes 84-columns of fuel elements, with 10 fuel elements in each column. Reflector elements surround the fuel elements.

B. A 72-column, 10-layer, core which produces 410 MW(t). This configuration is a variation of the previous 350 MW(t) commercial design, incorporating 6 additional fuel columns and a somewhat higher power density. It is most like the reactor design being proposed for the NPR. It utilizes the same diameter reactor vessel as the previous 350 MW(t) design and the NPR design but differs in steam generator size, hot duct diameter, and lower plenum height as a consequence of the increased power rating.

C. A 90-column, 10-layer, 450 MW(t) core. This configuration is a variant on the Case A reference design which utilizes six extra columns of fuel within the same reactor cavity to reduce the power density.

D. A 90-column, 9-layer, 450 MW(t) core. This configuration utilizes 90 columns of fuel elements similar to Case C above, but has only 9 fuel elements within each column. The total core height and reactor vessel height is reduced accordingly. The 450 MW(t) power rating is achieved by increasing the power density.

E. A 90-column, 10-layer, 500 MW(t) core. This configuration is also similar to Case C above, but achieves 500 MW with an increased power density. The core height is the same as Case C, but the alternative has an increased steam generator size, hot duct diameter, and lower plenum height to reflect the increased power level and increased coolant flow rate associated with the higher power density.

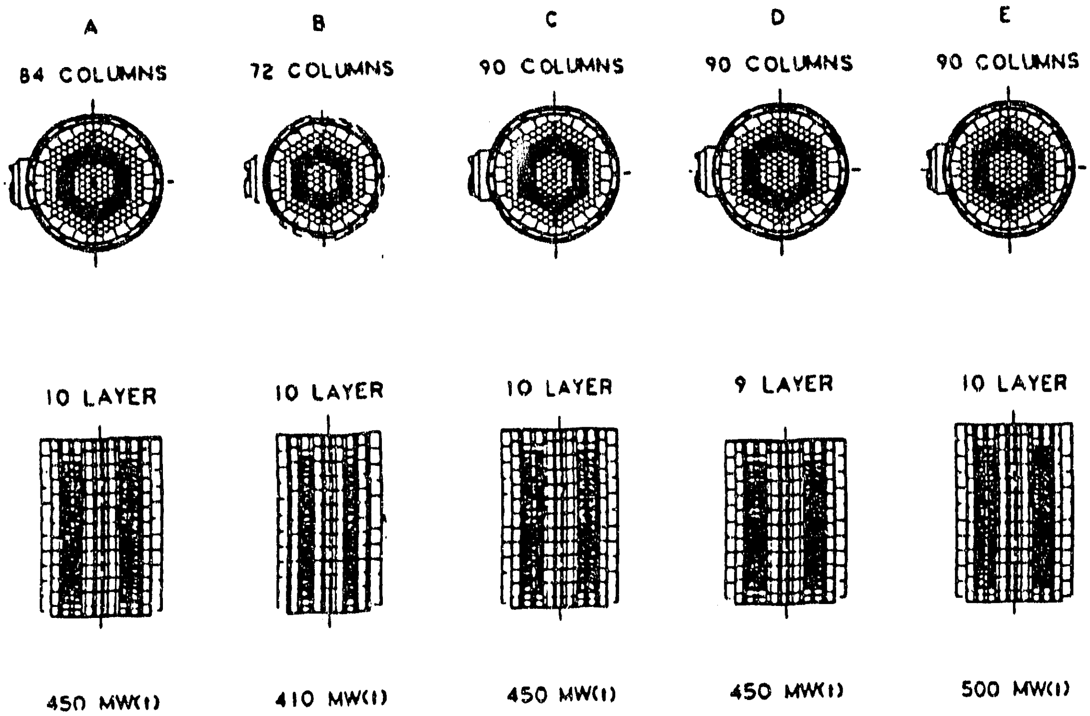


FIGURE 1

RANGE OF REACTOR SIZE AND CONFIGURATION ALTERNATIVES EVALUATED

COMPARISON OF ALTERNATIVES TO HIGHER WEIGHTED WANTS

The alternatives were ranked relative to the wants. For each want the *best* alternative(s) was identified followed by the others as judged in qualitative categories of *better*, *good*, and *ok*.

Provide Cost Margin Relative to Coal (high weight)

Comparative cost trends were calculated with a model which employs the same cost trend algorithms used in the CRS as supplied by program participants for their scopes of responsibility. These cost trends were for the n^{th} plant and were conducted using approximate methods to efficiently compare design options. The costs are in 1989 dollars and are adjusted to a replica plant estimate.

The three most significant factors affecting cost, in order of importance, are core power, reactor vessel size, and core height. Figure 2 shows the total busbar cost for the five configurations of this study. The 84-column, 450 MW(t) design (Case A) has a 14% cost improvement over the 350 MW(t) reference. The best configuration from a cost standpoint is the 500 MW(t) Case E having a 19% cost improvement. Figure 3 shows the capital cost for the five configurations of this study. The cost changes from the reference are essentially the same with the largest difference being a 19% capital cost improvement for the 500 MW(t) design (Case E).

The 84-column, 450 MW(t) design (Case A) is in the middle of the cost range along with the two other 450 MW(t) configurations. A cost savings of 3% is associated with improved thermal conditions of temperature and pressure and more effective design selections. The remaining 11% is due to the economy of scale.

Case B, the 410 MW small reactor vessel configuration, is 3% more expensive than Case A. This is due to lower power with economy of scale working against it. There is some cost advantage due to the smaller reactor vessel. The savings for this configuration are in the vessel system, reactor system, fuel handling system, and reactor building. These savings are not enough to overcome the decrease in power and this case is right at the capital cost must requirement.

Case C, the 90-column, 10-layer 450 MW(t) core configuration, is slightly more expensive (0.2%) than Case A. The added fuel fabrication cost due to 60 additional fuel blocks is greater than the savings in reduced core side reflector and circulator power.

The 9 layer core configuration of Case D is 1% better than Case A. A number of areas are helped by this change. In decreasing order of savings, they are: reactor building, reactor vessel, core barrel, fuel fabrication, core reflectors, circulator power, and Reactor Cavity Cooling System (RCCS).

Finally, Case E, the 500 MW core configuration, is 6% better than Case A. This is almost all due to the economy of scale. The capital costs do not go up as much as the electrical output. Savings in fuel fabrication cost contribute 0.2% toward the total. This is due to higher power density overcoming the effect of 60 additional fuel blocks.

FIGURE 2

OPERATING COST COMPARISON OF THE ALTERNATIVE DESIGNS

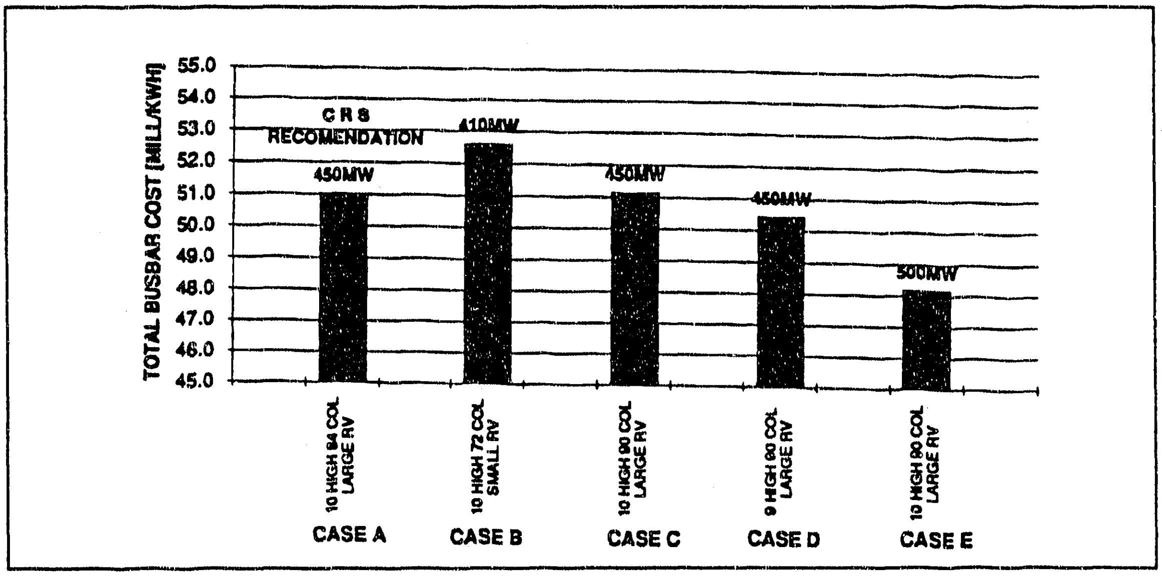
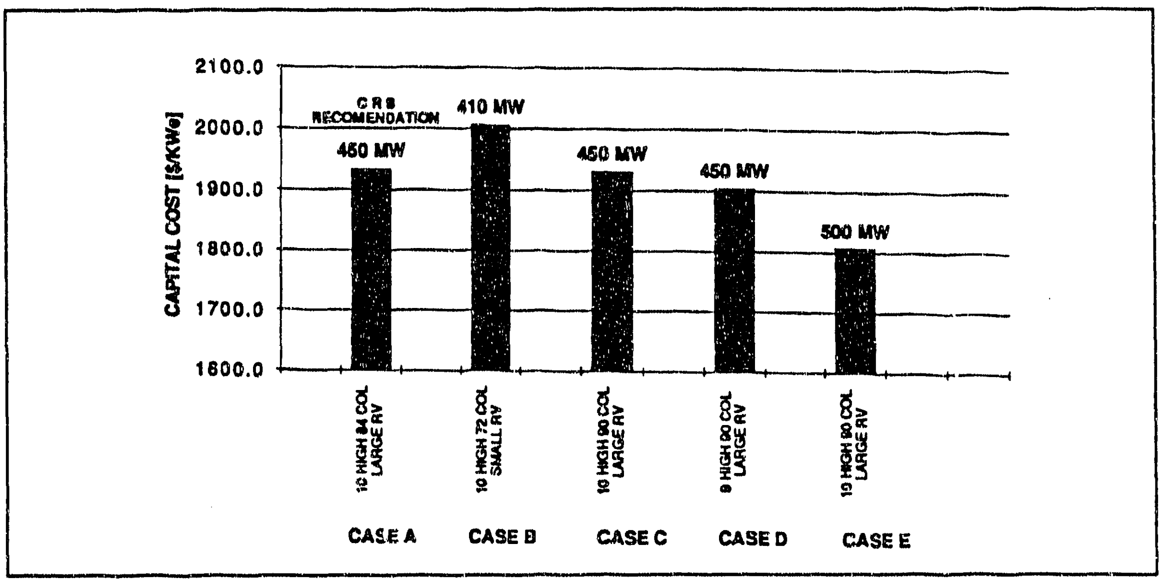


FIGURE 3

CAPITAL COST COMPARISON OF THE ALTERNATIVE DESIGNS



Utilize Development Cost Benefits of NPR (moderate weight)

All of the commercial alternatives described benefit economically from the technology transfer from the 350 MW(t), 66-column, 10 layer MHTGR-NPR. It is expected that the NPR will provide the design methods, the validation and verification of computer codes used in the design, much of the required technology development, and many of the design studies and details that would be used in any of the alternatives. Furthermore, the NPR could provide the prototype plant in which the performance of the fundamental safety features of the MHTGR is confirmed. Therefore, this evaluation was limited to evaluating the alternative core configurations for physical identity of components with their NPR counterparts. It is recognized that even though physical identity is achieved, differences in the design conditions for that component will exist as a result of differences in the duty cycle, seismic level, or other plant component design (such as the RCCS), and must be addressed in the design development.

Of the alternatives considered the 72-column, 10-layer 410 MW(t) core provides the most commonality with the current NPR design. The reactor vessel is essentially identical, having the same diameter and only a slightly increased height to accommodate a larger hot duct, lower plenum and cross vessel diameter. The metallic reactor internals (other than the hot duct) are also essentially identical, with only a minor difference in the height of the core lateral restraint. The graphite permanent reflector will be identical and the graphite core support will differ only slightly in height. The neutron control assemblies, in-core flux monitoring and much of the refueling equipment will be identical because of the commonality in control rod locations and NCA penetrations used for refueling. Reactor service equipment would also be identical. Core instrumentation required for the commercial plant would be identical to some of that which may be anticipated for the NPR plant. The plant protection hardware would also be identical, although the software would be different to reflect the difference in trip requirements. The shutdown coding heat exchanger (SCHE) may also be physically identical even though they may have different safety classifications. The core design is substantially different due to NPRs inclusion of target fuel elements and high enriched fissile fuel. The steam generator would be different to accommodate the higher power level, the circulator would be different because of the desirability of utilizing magnetic bearings, and other plant components would be different because of different requirements and/or different power levels.

The extent of commonality is slightly less with all of the other alternatives. The larger core and larger reactor vessel eliminate some of the physical identity obtained with the 72-column configuration. However, some of the core instrumentation, protection hardware, reactor service equipment, and refueling equipment would be common. For the 450 MW(t) alternatives, the SCHE would be common. However, for the 500 MW(t) core, it may be expected that the SCHE will also be different and the extrapolation from the 350 MW(t) NPR components such as the steam generator and circulator is greater.

The assumption that the MHTGR-NPR project precedes the commercial MHTGR provides a significant advantage in the development and construction costs for all the alternative commercial designs. The cost advantages are realized because of the similarity of major components and the learning curve by members of the contractor teams.

In summary, the most beneficial alternative on commonality is Case B which is based on a 72-column core. This alternative utilizes the same reactor vessel size as the MHTGR-NPR. The other alternatives all utilize a larger reactor vessel size to accommodate the 84-column or 90-column cores.

Provide Margin on Pressurized Conduction Cooldown Temperatures (moderate weight)

The pressurized conduction cooldown (PCC) and depressurized conduction cooldown (DCC) are important classes of events which challenge heat removal and therefore the control of radionuclides. The PCC and DCC events occur when the Heat Transfer System (HTS) and Shutdown Cooling System (SCS) have both failed to perform respective functions of providing forced cooling of the core. Decay heat is then removed by thermal radiation and natural convection from the reactor vessel to the natural circulation air-cooled RCCS. The thermal transients for these two accidents use conservative values for the decay heat which are 12% higher than nominal. The 12% is composed of two parts: 2% is for the assumed uncertainty in power level instrumentation, and 10% accounts for the uncertainty in decay heat, material properties and calculation methods.

As part of this study to determine the best overall core configuration, PCCs and DCCs were evaluated for all five core alternatives. Table 3 summarizes the system parameters, temperatures of key components and component limiting temperatures during PCCs for the five cases. The initial pressure, and core inlet and outlet temperature are the same for all concepts. In addition, the radial and axial zoning was adjusted to flatten power profiles and reduce the maximum core peaking factor.

The PCC event is typically initiated by loss of offsite power and turbine trip plus failure of the SCS to start; the reactor trips and inserts the operating control rods making the reactor subcritical. With the HTS and SCS not available to provide forced cooling to the reactor, decay heat is then removed by thermal radiation and natural convection from the reactor vessel to the RCCS.

Of the key component peak temperatures shown in Table 3 for the various cases, the fuel, operating control rod and upper plenum shroud temperatures have both the least sensitivity to core configuration/power changes and have the greatest margin to component temperature limits. The two key parameters, which are the most sensitive to core configuration/power changes and are closest to component temperature limits during PCCs, are vessel temperature and core barrel temperature. These two parameters were examined to determine the best core configuration from the PCC standpoint.

The PCC results given in Table 3 indicate that all five configurations meet all appropriate component temperature limits with acceptable margins. Indeed there is only minor variation in the peak vessel and core barrel temperature for the different configurations.

From the PCC standpoint, the 72-column, 410 MW(t) core Case B, is marginally the best design because it offers the most margin to the vessel temperature limit while still offering an acceptable margin for the core barrel temperature. However, the 84-column 450 MW(t), Case A design also offers large margins to both the vessel and core barrel temperature limit.

For a given core power there is negligible difference between the recommended 84-column core, Case A and a 90-column core Case C as shown in Table 3. A 9-layer high core Case D increases the maximum core barrel temperature approximately 20°F and has a negligible effect on maximum vessel temperature as compared to a 10 layer high core Case C. At 500 MW(t), Case E, is acceptable but reduces margin to both the vessel and core barrel temperature limits when compared to the same design configuration at 450 MW, Case D. The margin to the vessel and core barrel temperature limits is only 10°F for Case E.

TABLE 3

ALTERNATIVE CORE CONFIGURATION DESIGN COMPARISONS

	Case A	Case B	Case C	Case D	Case E	
Power, MW(t)	450	410	450	450	500	
Fuel columns	84	72	90	90	90	
Core layers	10	10	10	9	10	
Power density, w/cc	6.0	6.3	5.6	6.2	6.2	
Vessel ID, ft.	23.7	21.5	23.7	23.7	23.7	
Pressure, psia	1025	1025	1025	1025	1025	
Core inlet temperature, °F	550	550	550	550	550	
Core outlet temperature, °F	1300	1300	1300	1300	1300	
<u>Peak Pressurized Conduction Cooldown Temperatures</u>						Limit
Fuel, °C	592	603	618	640	622	~ 1600
Vessel side wall, °F	760	739	760	761	790	800
Upper plenum shroud, °F	1354	1420	1358	1383	1420	1500
Core barrel, °F	1325	1373	1330	1348	1390	1400
Operating control rod, °F	1478	1520	1496	1532	1578	1800

<u>Provide Margin on Depressurized Conduction Cooldown Temperatures (moderate weight)</u>

The DCC event is typically initiated by a small primary coolant leak 0.32cm^2 (0.05in^2) near the top of the reactor vessel. The reactor trips automatically on low reactor pressure and the side reflector operating control rods are inserted. The HTS fails immediately after the initiating event and the SCS fails to start on demand. The RCCS then removes decay heat from the vessel by natural convection and thermal radiation. The fuel temperature is the limiting component temperature for the DCC event. A comparison of the peak fuel temperature as a function of power is shown in Figure 4. The peak fuel temperature for the various core configurations are also tabulated in Table 4.

Because of the 1600°C limit on the fuel temperatures, the 9-layer high core, the 500 MW 10 layer high core, and the 72 column, 410 MW small reactor vessel designs are estimated to be right at the fuel temperature requirements. Case A and Case C have only minor differences in the core designs. As one would expect, Case C, the core with the most fuel columns, (i.e., the lowest average core power density), has slightly more margin on peak fuel temperatures for the DCC event. However, with respect to the peak operating control rod temperatures Case A without the six extra columns on the active core periphery results in the lowest temperatures. Case C is ranked next followed by the other three.

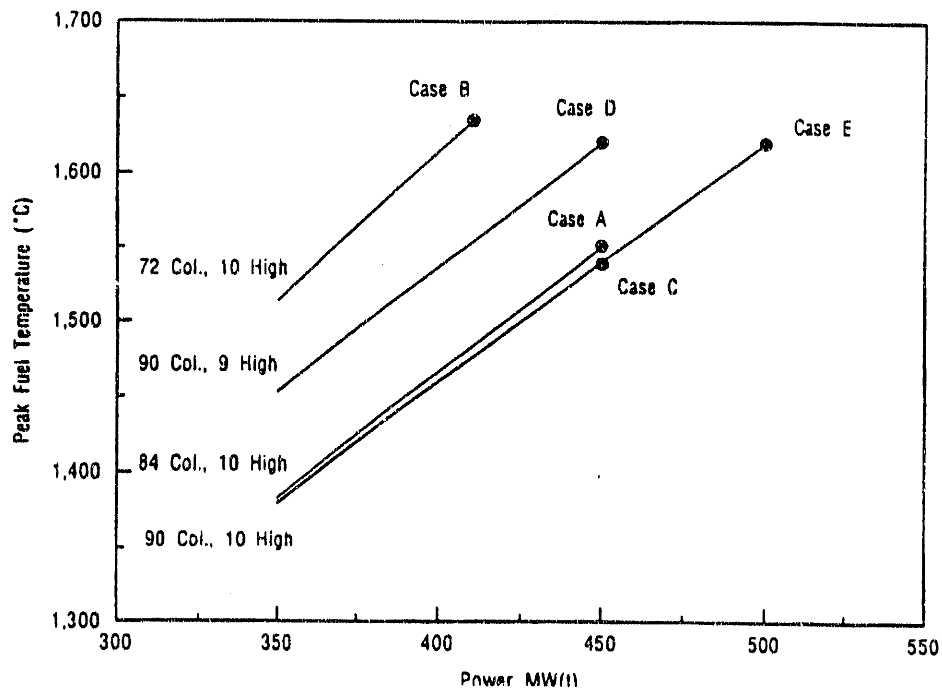
TABLE 4

COMPARISON OF ALTERNATIVES FOR DCC FUEL TEMPERATURE WANT

Peak Depressurized Conduction Cooldown Temperature	Case A	Case B	Case C	Case D	Case E	Limit
Average Fuel, °C	1240	1350	1230	1300	1325	--
Maximum Fuel, °C	1550	≤ 1630	1540	< 1620	< 1620	1600
Operating Control Rod, °F	2050-2150	≥ 2285	2300-2400	2190-2290	2210-2310	~2150
Side Wall Vessel, °F	735	870	740	795	845	900

FIGURE 4

COMPARISON AT PEAK FUEL TEMPERATURES DURING DEPRESSURIZED CONDUCTION COOLDOWN AS A FUNCTION OF POWER



CONCLUSIONS

Five core configurations have been examined in terms of desirable objectives related to plant economics, passive safety, and component design margins. The results of the overall ranking of the five core configurations is that Case A, the 450 MW(t), 84-column, 10 layer core previously selected in the CRS remains the best configuration. While not the highest rated in every category, Case A has attractive economics and retains the passive safety margins which are higher rated wants. A close second is Case C, the 450 MW(t), 90-column, 10 layer configuration. However, it has slightly less cost margin and less flexibility in locating the outer control rods. The remaining three cases are right at the 1600°C fuel limit during conduction cooldown which is too close at this point in the preliminary design. Case B which retains the same size vessel as the 350 MW(t) NPR has a number of advantages over and above commonality, in the area of component design margin. Its chief disadvantages, however, are in the higher weighted areas of plant economics and margin on the passive safety DCC temperatures.

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