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NGNP Reactor Parametric Study

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Disclaimer

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AREVA NP Inc.

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1.0 Introduction

This report presents the results of an evaluation of the interrelationships between key NGNP reactor design and operating parameters, using the current AREVA NGNP reactor reference design as a basis. The work was performed in accordance with the requirements of Subtask 2.2 “Reactor Parametric Study” of Reference 1.

Due to the limited time allotted to complete this scope of work, development of new, unreported information was necessarily limited and consisted mainly of exercising existing simple models of NGNP behavior. Most of the information used to support the parametric analyses presented here is drawn from prior work conducted by AREVA for the NGNP project, documented in References 2-7.

2.0 NGNP Design Limits

Development of the parametric relationships between reactor power, inlet temperature, outlet temperature, and core power density, and their impact on key reactor components, was performed by examining the sets of state-points which correspond to the limiting conditions for the components.

Four reactor power configurations were considered:

- A 600 MWth reactor with a 102 column core,
- A 450 MWth reactor with a 102 column core,
- A 450 MWth reactor with an 84 column core, and
- A 300 MWth reactor with an 84 column core.

For each of these configurations, a series of design limits was established by identifying the sets of inlet temperature and outlet temperature conditions which would correspond to the limiting condition for each of the reactor components considered. The results of this process was a group of four graphs of inlet temperature vs. outlet temperature, one for each power configuration, on which are plotted lines which represent the limiting condition for the various components. These graphs are presented in Figures 3-1 to 3-4.

It is important to understand that these limiting condition lines are based on numerous assumptions, most notably that design conditions not specifically included in the parametric evaluation are at the value reflected in the current AREVA NGNP baseline configuration (Reference 8). For example, reactor primary pressure is assumed to be 5 MPa. Changes in this value would have impacts on the limiting lines presented for both the circulators and the reactor vessel.

Because of the necessity of using these assumptions in this evaluation, the results should not be considered to be hard limits describing where the NGNP reactor design can operate, but rather as general guidelines for detailed design development. Should a desired state-point be slightly beyond a given limiting line, it does not necessarily mean the design should not be considered, but rather that more detailed assessment of the particular situation should be considered.

The detailed discussions of the limitations for each component presented below will identify the key assumptions used to establish the limit.

2.1 Fuel – Normal Operation

Steady-state fuel temperatures for normal operation were calculated using the model developed to support the Heat Transport System configuration matrix evaluations in Reference 6. This model calculates both core average and maximum fuel temperatures based on core inlet temperature, core outlet temperature, and reactor power, amongst other variables.

To establish the line representing the design limit for fuel normal operation, sets of core inlet and outlet temperature, for each power level and core size, were identified that resulted in an average fuel temperature of approximately 1250°C and a maximum fuel temperature of 1350°C. Table 2.1-1 presents the results of this evaluation. It can be seen that the core outlet temperatures which yield a maximum fuel temperature at the 1350°C limit are lower than those that meet the core average temperature limit, and therefore present the limiting outlet temperature for the give core inlet temperature. These lower temperatures were used to establish the limiting fuel temperature line.

Table 2.1-1 Fuel Temperature Limits Data Summary

Tin	Maximum Tout for Max Fuel Temp <= 1350°C				Maximum Tout for Avg Fuel Temp <= 1250°C			
°C	600 MW 102 Col	450 MW 102 Col	450 MW 84 Col	300 MW 84 Col	600 MW 102 Col	450 MW 102 Col	450 MW 84 Col	300 MW 84 Col
200	784	807	792	821	976	1000	984	1016
250	808	830	816	844	985	1009	993	1024
300	831	853	839	868	993	1017	1002	1032
350	854	876	862	890	1002	1026	1010	1040
400	876	898	884	912	1011	1034	1019	1048
450	898	920	906	934	1020	1043	1028	1057
500	920	942	928	956	1029	1051	1037	1065
550	942	964	950	977	1038	1060	1046	1074
600	963	985	971	998	1047	1069	1055	1082

2.2 Fuel – Accident Conditions

Previous analyses have demonstrated that the limiting accident, from an overall plant design standpoint, is typically the depressurized conduction cooldown (DCC) event, as this event usually results in the highest fuel and reactor vessel temperatures. For this reason, several DCC analyses and sensitivity studies have been conducted in the course of AREVA's work on the NGNP project. These results have been used in this evaluation.

For the 600 MWth 102 column core case considered in this study, the expected accident fuel temperature line has been plotted on Figure 3-1. This line is based on the combinations of inlet and outlet temperature which yield an estimated maximum fuel temperature of 1650°C, using input parameters which are deemed conservative for evaluation of this parameter. This line clearly shows a significant limitation in allowable design space at higher inlet and outlet temperatures. This result is consistent with the results discussed in Reference 4, where a maximum reactor power of 565 MWth was recommended to preserve the ability to operate at these higher temperature combinations. Figure 3-5 presents the design limits graph calculated for a reactor power level of 565 MWth and a 102 column core to demonstrate this effect.

For the remaining cases considered in this report, individual DCC cases calculated at or near the appropriate state points indicate that maximum fuel temperatures are well below the limit of 1650°C considered for this study. As such, associated design limit lines would be expected to be outside of the limits imposed by other considerations and no limit lines associated with accident fuel performance are provided on Figures 3-2, 3-3, and 3-4.

2.3 Reactor Vessel – Normal Operation

Two different reactor vessel materials are considered, SA508 steel (PWR vessel material) and modified 9Cr1Mo steel. Limits for both are included.

Unlimited use of SA508 material is currently permitted up to 371°C during normal operation under the conditions defined in ASME Code Case N-499-2. Though the reactor vessel may, in places, be in direct contact with the primary coolant helium at core inlet temperatures, heat transfer considerations result in maximum calculated vessel wall temperatures about 50°C lower than the core inlet temperature. An inlet helium temperature of 400°C could be envisioned as limiting for the RPV based on these conditions, including consideration of additional margin by assuming the materials' maximum steady state operating temperature limit is 350°C.

9Cr1Mo is covered by ASME Section III, but its use for RPV application would require extending subsection NH of the Code to heavy section forgings. The regulatory acceptance of this material may however be an issue, especially for higher core inlet temperatures, which would require an agreed upon definition of negligible creep conditions for this material. AREVA has performed a stress analysis investigation for this material at a system pressure of 6 MPa and a maximum design temperature of 460°C in Reference 2. It was demonstrated that the calculated stress intensity of the material satisfies primary and secondary design limitations. Based on this analysis, an inlet helium temperature limit of 500°C could be envisioned for a 9Cr1Mo RPV based on these conditions and assuming that the vessel temperature will be about 50°C lower than the core inlet temperature, as demonstrated for the SA508 case.

In addition to use of these two materials for passively-cooled reactor vessels, there has been some interest shown in utilizing an actively cooled SA508 reactor vessel to gain the higher temperature performance benefits of the 9Cr1Mo material without the associated development risk. For the purposes of this evaluation, it is considered possible that an active cooling system would be able to acceptably perform this function, therefore the limiting line for a 9Cr1Mo reactor vessel is also considered to be appropriate for an actively cooled SA508 vessel. Obviously, considerably more detailed analysis would be required to verify this assumption should such a system be contemplated.

2.4 Reactor Vessel – Accident Condition

Evaluation of design limits associated with the accident performance of the reactor vessel is a complicated task. For example, ASME code limits for SA508 material allow:

- Unlimited exposure to 371°C
- 3000 h maximum duration at temperatures between 371 and 427 °C
- 1000 h and no more than 3 events at temperatures between 427 and 538°C

For this reason, defining a single line representing the design limit, as done in other areas of this study, may not be appropriate, and would in any case require an effort well beyond the scope of this study. As such, no lines representing reactor vessel accident limits are provided on Figures 3-1 to 3-5.

Based on work that AREVA has previously performed for the NGNP project, it is estimated that some of the inlet and outlet temperature combinations at the higher reactor power levels may result in reactor wall temperature and time profiles that may be approaching these limits for certain assumptions regarding the numbers and types of events over the reactor lifetime. However, as far as the conclusions to this study are concerned, it is expected that if reactor designs are implemented within the constraints provided by the other design limits discussed in this report, reactor temperature limits should not become limiting for reasonable event sequences.

2.5 Intermediate Heat Exchanger

Current operational experience described in Reference 6 indicates that use of Alloy 617 in heat exchanger applications over the temperature range 750°C to 850°C provides acceptable operational performance. At higher temperatures, environmental effects, such as oxidation, carburization, and decarburization, become life-limiting considerations. Given the robust nature of the tubular, helical heat exchanger design proposed for the AREVA NGNP plant, operation at a maximum temperature of 900°C is considered to be achievable without significant detrimental impacts on IHX lifetime.

2.6 Helium Circulators

Primary and secondary loop helium circulator powers required for normal operation were calculated using the model developed to support the Heat Transport System configuration matrix evaluations in Reference 6. This model calculates both primary and secondary circulator powers based on core inlet temperature, core outlet temperature, and reactor power, amongst other variables.

To establish the line representing the design limit for circulator performance considered in this evaluation, several simplifying assumptions were made. It was assumed that the number of both primary and secondary loops was equal and was driven by the number of required IHXs. Based on the information in Reference 6 which indicates a maximum feasible IHX size of approximately 300 MWth, two loops were assumed for the 600 MWth and 450 MWth reactors and a single loop was assumed for the 300 MWth reactor. It was also assumed that only a single circulator was used within each loop. Use of these assumptions means that the limiting circulator performance lines presented on the below graphs should only be used to identify general trends between the cases considered, since fairly easily achieved design solutions can be employed to extend the acceptable operation envelope well beyond the reported values.

The results of the calculations indicated that the power requirements for the secondary circulator presented the most limiting consideration. Reference 8, which documents the current AREVA NGNP baseline configuration, indicates a maximum feasible secondary circulator power of 16 Mwe. A limiting set of inlet and outlet temperature conditions for each power configuration were calculated based on this limiting circulator power. Table 2.6-1 lists these temperature pairs. The table also indicates, for each pair, the associated required primary circulator power and total fraction of plant output required to power the circulators.

An additional design limit was identified for the circulators, as documented in Reference 3. At temperatures above 540°C, the Inconel 718 material used in the impellers begins to experience high temperature creep. To avoid the lifetime impacts of this phenomenon, the core inlet temperature was limited to this value and below.

Table 2.6-1 Circulator Power Limits Data Summary
(Based on Secondary Circulator Power Limit of 16 MWe)

Tin	Reactor Power = 600 MWth			Reactor Power = 450 MWth			Reactor Power = 300 MWth		
	Tout	Primary Circulator Power - MWe	Circulator Power Fraction* - %	Tout	Primary Circulator Power - MWe	Circulator Power Fraction - %	Tout	Primary Circulator Power - MWe	Circulator Power Fraction* - %
200	457	7.5	17	433	7.5	23	457	7.5	17
250	528	7.3	17	503	7.2	23	528	7.3	17
300	599	7.0	17	572	7.0	23	599	7.0	17
350	669	6.9	17	640	6.8	22	669	6.9	17
400	739	6.7	17	708	6.7	22	739	6.7	17
450	808	6.6	17	775	6.6	22	808	6.6	17
500	876	6.5	17	842	6.5	22	876	6.5	17
540	930	6.4	17	895	6.4	22	930	6.4	17

* Note – Circulator power fraction is based on an assumed electrical generating efficiency of 45%

2.6.1 System Pressure Impacts

One important circulator performance parameter that was not varied in this parametric evaluation was system pressure. This value was assumed to be equal to the current AREVA reference value of 5 MWth as specified in Reference 8. This rationale for use of this value in the AREVA base design is the result of a trade-off of circulator performance against reactor vessel performance and overall feasibility (Reference 6). Should other, higher system pressures be assumed, the expected power requirements for the circulators would be reduced at the expense of higher reactor vessel stresses, or increased reactor vessel wall thickness, both of which present additional challenges.

2.7 Core Graphite

At core inlet temperatures less than 150°C, the release of stored energy accumulated in graphite due to the Wigner effect is a concern for a graphite-moderated reactor like the NGNP. The low-temperature release of stored energy in graphite is not considered to be an issue if the core inlet temperature is greater than 250°C. Graphite annealing that would occur over the normal range of NGNP operating temperatures would relieve the buildup of stored energy and enhance graphite performance. As such, for the purposes of this study, the minimum core inlet temperature boundary is set at 250°C.

3.0 Summary of Results

Figures 3-1 to 3-4 present the results of the evaluations described in Section 2 of this report. Each depicts a graph of core inlet temperature versus core outlet temperature for each of the four power configurations considered. Upon these graphs are plotted lines that depict the limiting combinations of inlet and outlet temperature for each pf the reactor components evaluated. In most cases, these lines depict maximum conditions, that is temperature combinations below or to the left of the line are allowed. The circulator line depicts a minimum, in terms of power and a maximum in terms of temperature, therefore operation above and to the left of the line is allowed. The core graphite line depicts a minimum, therefore operation to the right of the line is allowed.

Figure 3-5 presents a similar graph for the power configuration recommended in the AREVA Power Level Special Study, Reference 4.

Figure 3-6 presents a compilation of the allowable design areas from each of the preceding figures, allowing easy comparison of the impacts of the various power configuration assumptions.

Figure 3-1 NGNP Design Limits

600 MWth 102 Column Core

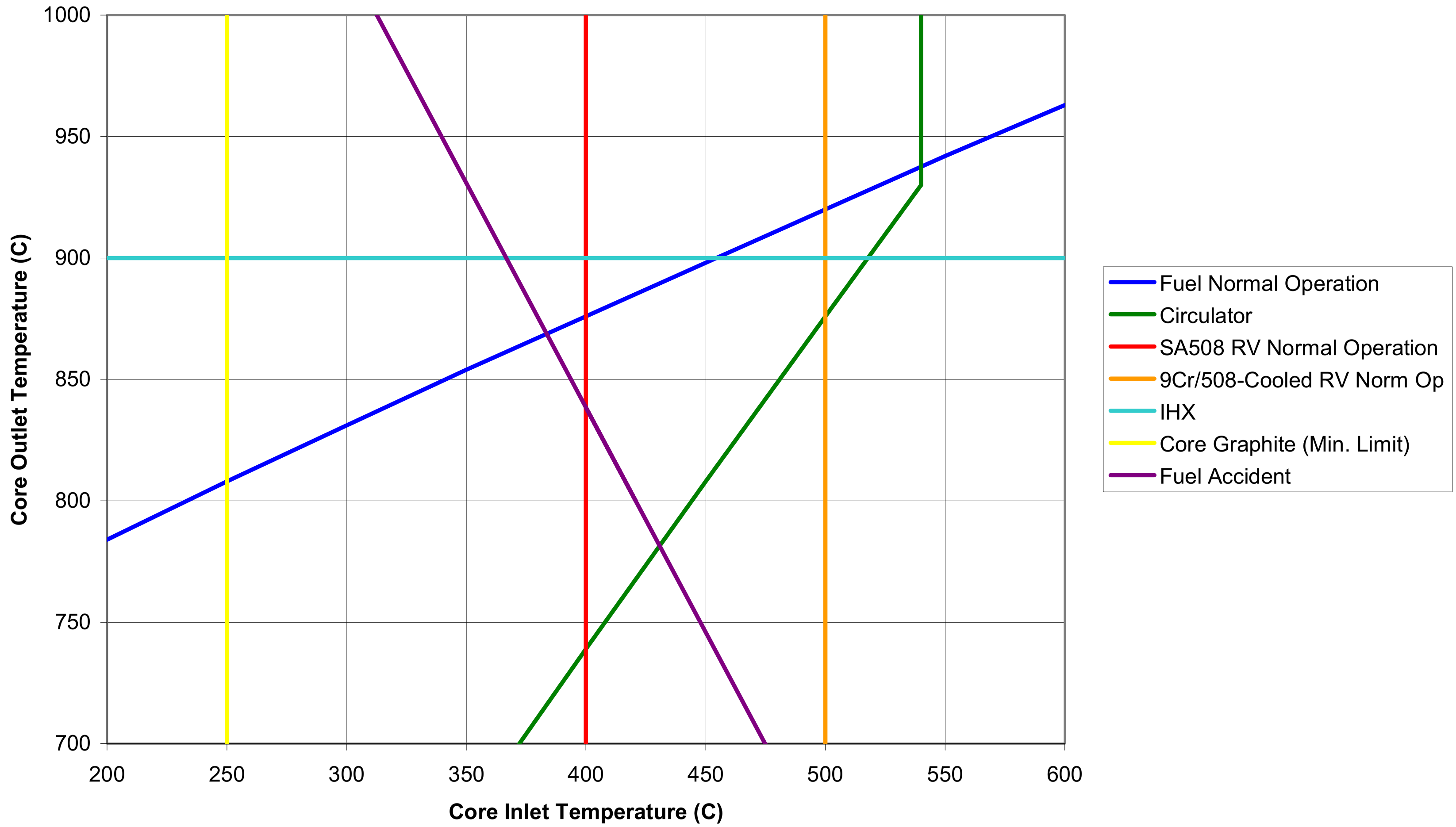


Figure 3-2 NGNP Design Limits
450 MWth 102 Column Core

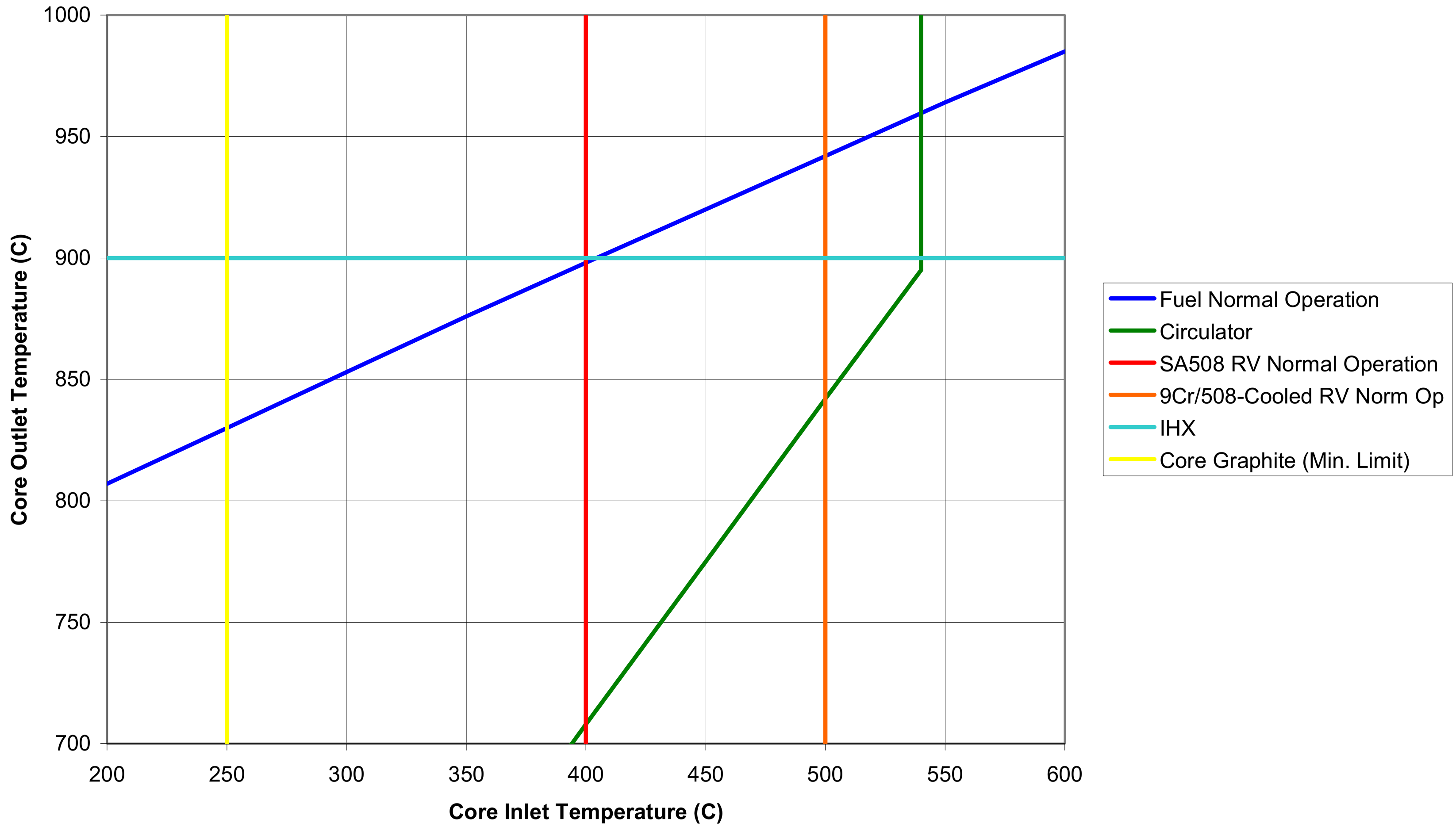


Figure 3-3 NGNP Design Limits

450 MWth 84 Column Core

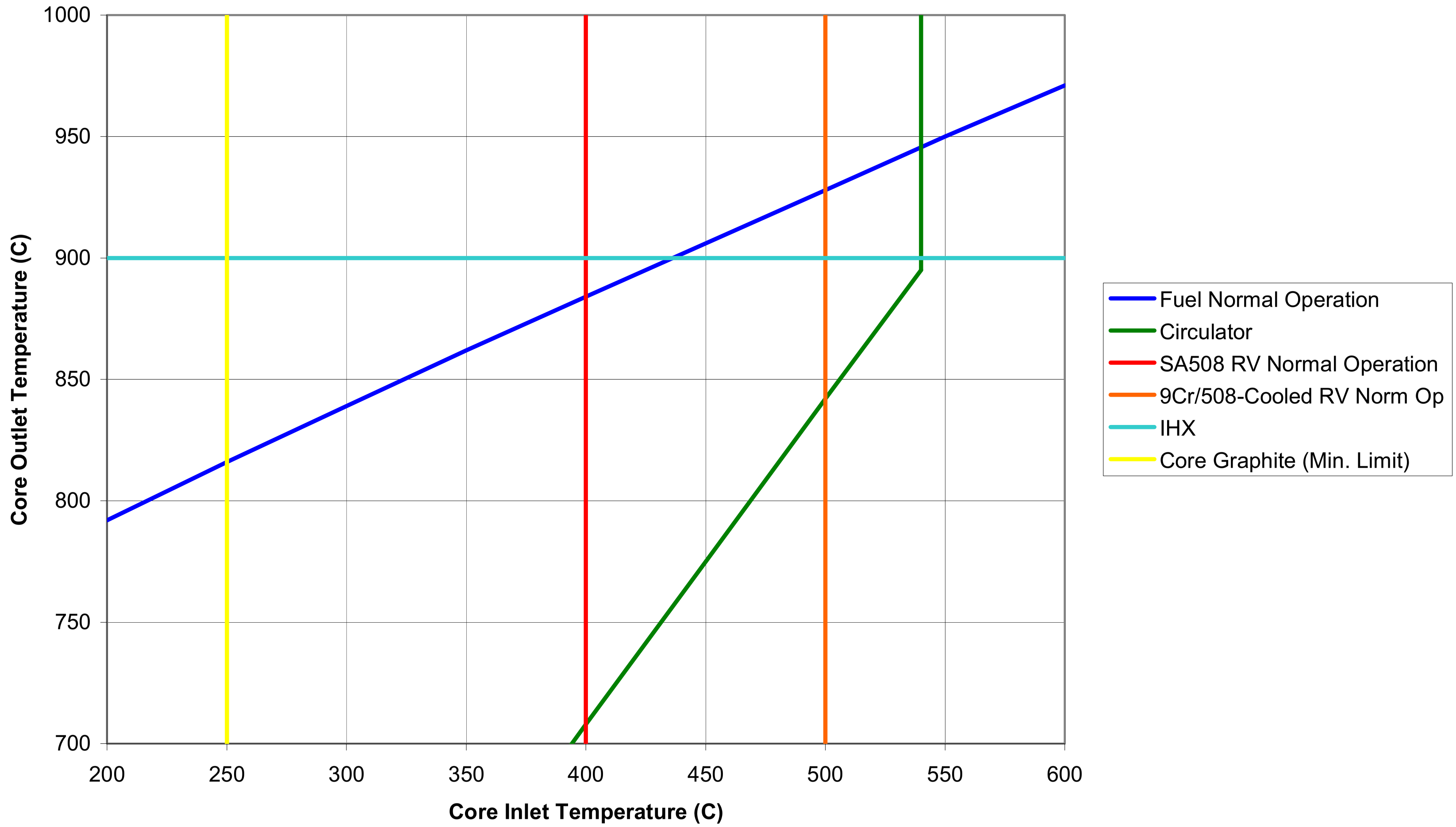


Figure 3-4 NGNP Design Limits
300 MWth 84 Column Core

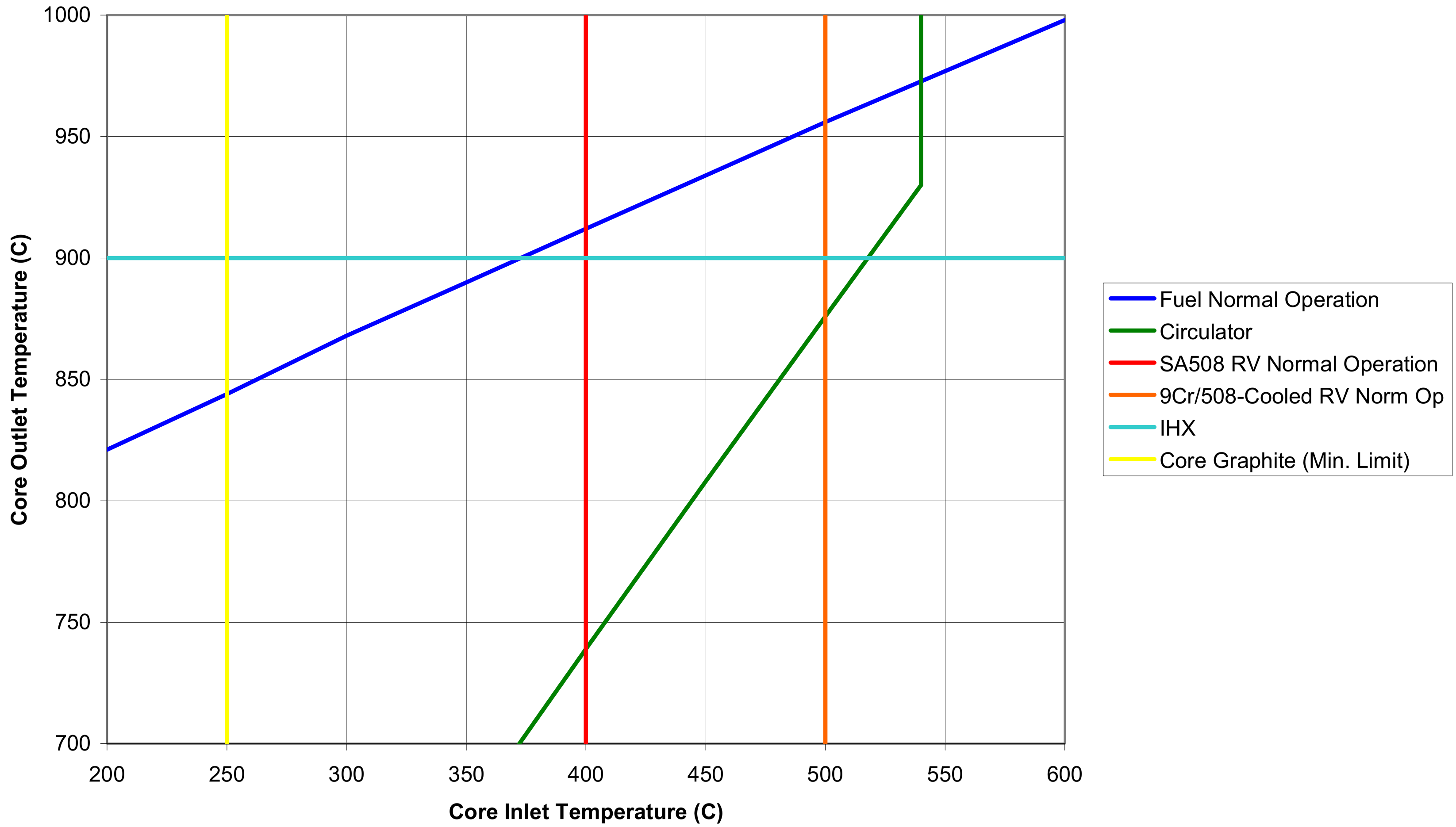


Figure 3-5 NGNP Design Limits
565 MWth 102 Column Core

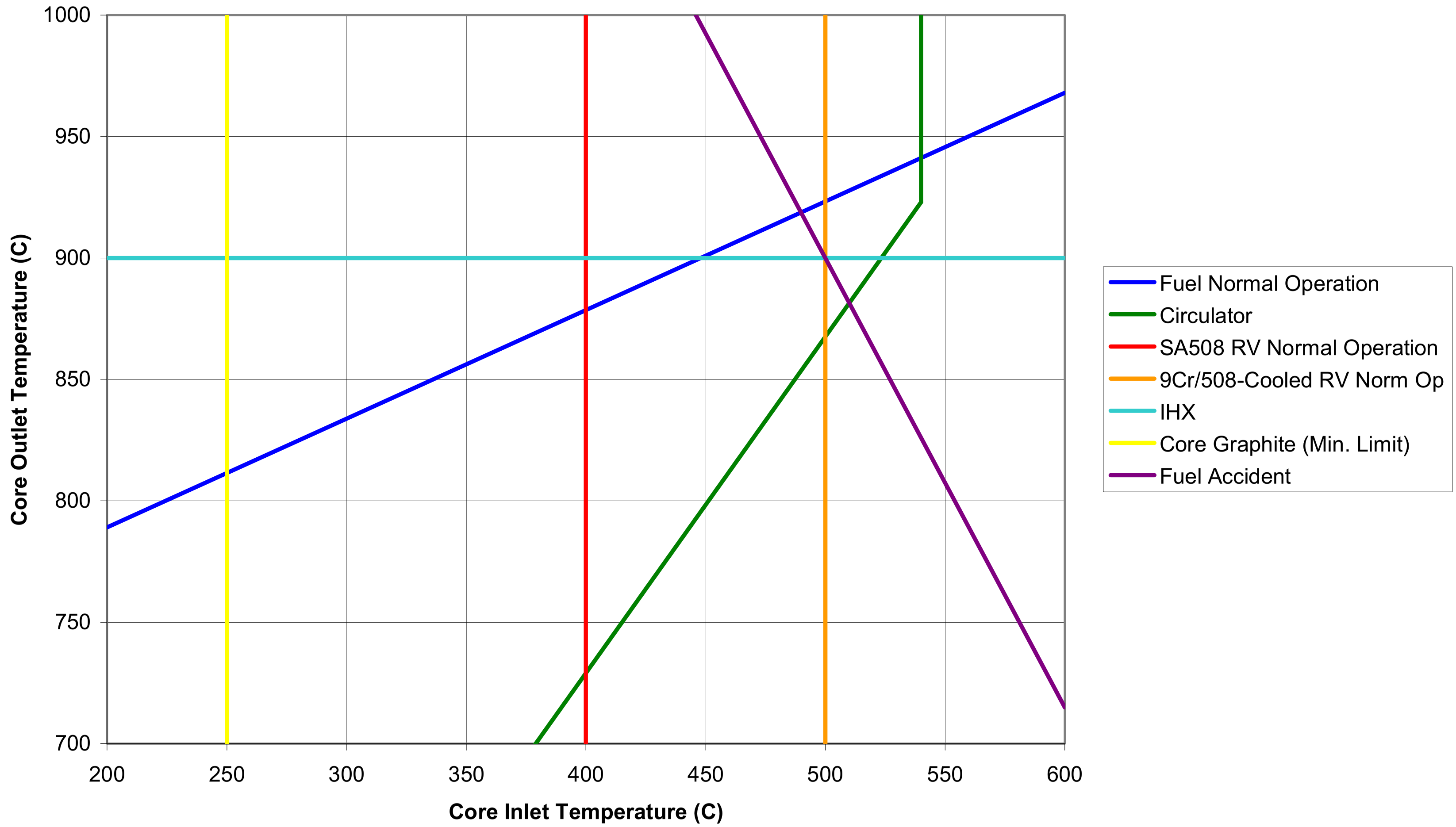
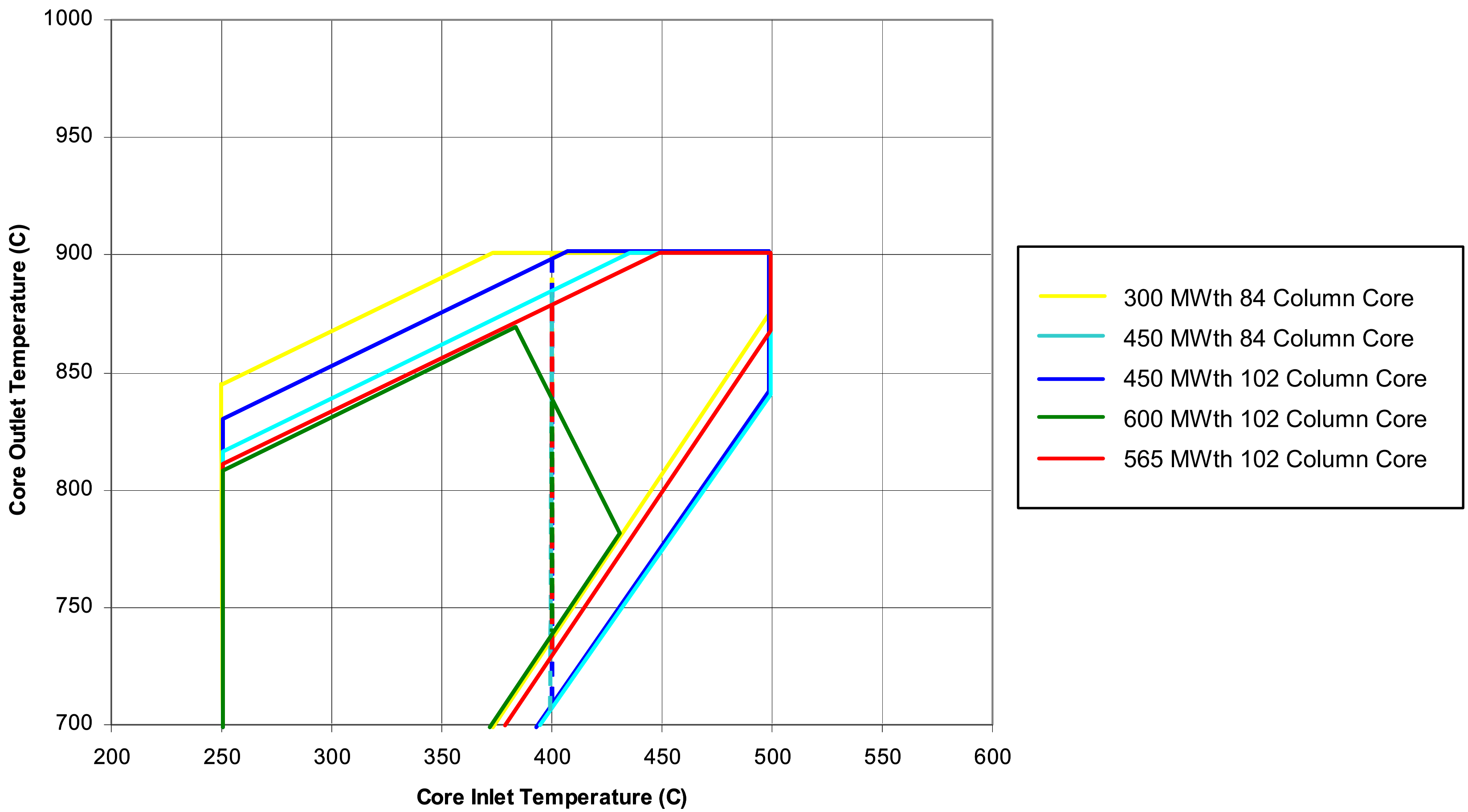


Figure 3-6 Composite NGNP Design Limits



4.0 References

1. NGNP WBS Activity NHS 90, "Reactor Parametric Study and Review of the Recommendations for the operating Conditions and Configuration of the NGNP Project Demonstration Plant", PCN05-21-08 to Contract 75310.

2. AREVA Report 12-9076324-001, "NGNP RPV and IHX Pressure Vessel Alternatives", April 2008.

3. AREVA Report 12-9075581-000, "NGNP Risk Evaluation of Major Components", April 2008.

4. AREVA Report 12-9045442-001, "NGNP With Hydrogen Production Power Level Special Study Report", April 2007.

5. AREVA Report 12-9045707-001, "NGNP Primary and Secondary Cycle Concept Study", April 2007.

6. AREVA Report 12-9076325-001, "NGNP – IHX and Secondary Heat Transport Loop Alternatives", April 2008.

7. AREVA Report 12-9077148-001, "NGNP Fuel Design Special Study", April 2008.

8. AREVA Report 51-9072396-000, "NGNP Conceptual Design Studies Baseline Document for Indirect Steam Cycle Configuration", March 2008.