

《Technical Report》

## OPAT and OTAT Trip Setpoint Generation Methodology

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### OPAT 및 OTAT 트립설정치의 생산방법

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#### Abstract

Core safety limits define reactor operating conditions and parameters that will assure fuel rod and reactor system's integrity. Limiting safety system settings (LSSS) programmed into reactor protection system (RPS) then ensure a rapid reactor trip to prevent or suppress conditions which might violate the core safety limits. Generation of the LSSS must properly take into account uncertainties in both calculated and measured parameters in order to assure, with an appropriate degree of confidence, that the RPS will protect the core safety limits.

Reviewed in this report are Westinghouse RPS setpoint generation philosophy, methodology of safety limit development and LSSS generation procedure. The Westinghouse RPS trip setpoint generation methodology has been established based on the calculation of core safety limits and the selection of LSSS allowing appropriate uncertainties in a conservative manner. Such conservative values of setpoint assure a high degree of core protection against fuel melting and occurrence of DNB.

#### 요 약

원자로 안전한계 설정의 근본목적은 핵연료 및 원자로 계통의 건전성을 보장할 수 있도록 원자로 운전조건을 제한하는 데 있다. 원자로 보호계통은 원자로 운전변수들이 트립설정치에 도달하게 되면 원자로를 긴급정지시켜 운전조건이 안전한계를 초과하지 못하도록 한다. 따라서 이들 트립설정치의 생산을 위해서는 계산과 측정오차를 충분히 고려해 주어야 한다.

본 기술보고서에서는 웨스팅하우스 원자로 보호계통 트립설정치의 생산에 따른 기본원리와 노심 안전한계의 개발방법 및 트립설정치의 생산절차를 검토하였다. 웨스팅하우스 보호계통 트립설정치의 생산원리는 노심의 안전한계를 계산하고 측정 및 계산에 따른 불확실성을 충분히 고려하여 보수적인 트립설정치를 생산함으로써 핵연료의 용융과 DNB가 발생하지 않도록 하자는 데 있다.

**1. Introduction**

For a safe operation of pressurized water reactor (PWR), core safety limits must first be established to define operating conditions and parameters which will assure fuel rod and reactor system's integrity. Then, setpoints are generated for the reactor protection system (RPS) that will produce a reactor trip early enough to prevent or suppress conditions which might violate the core safety limits. Such setpoints called limiting safety system settings LSSS that are programmed into the RPS assure appropriate action if monitored values equal the nominal setting which are below LSSS. Generation of the LSSS must properly take into account uncertainties in both calculated and measured parameters in order to assure, with an appropriate degree of confidence, that the RPS will protect the core safety limits.

Included in this report are Westinghouse RPS setpoint generation philosophy, methodology of safety limit development and LSSS generation procedure along with the characterization of uncertainties.

**2. RPS Setpoint Generation Philosophy**

The fundamental purpose of a RPS is to prevent the release of radioactivity to the environment. The protection system includes the reactor trips, the engineered safety features actuation and certain interlocks. The reactor tripping functions insure that the reactor is automatically tripped whenever plant conditions monitored by nuclear and/or process instrumentation approach trip setpoints.

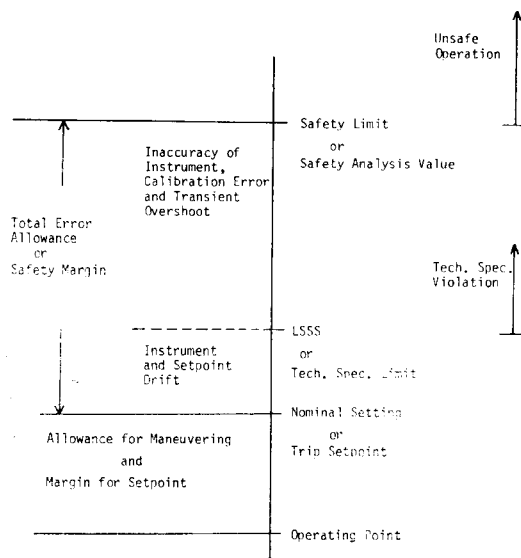
The RPS provides steady state and transient protection for the reactor core and primary coolant system, and assures that the following three safety limits are not violated:

- a) high reactor coolant pressure safety limit (110% of design pressure),
- b) departure from nucleate boiling ratio (DNBR) safety limit, and
- c) maximum linear heat generation rate (LHGR; kw/ft) limit to prevent centerline fuel melting.

Among the parameters above, only the reactor coolant pressure is directly measurable; the linear heat generation rate and DNBR must be determined from combinations of parameters that can be directly measurable. By monitoring these measurable parameters, the proximity of the core conditions to the specified safety limits can be established and the appropriate protection action can be initiated when required.

Setpoints in the Technical Specification are generally selected through the following procedure:

- a) Generate the "analysis value or safety limit" that is demonstrated to be safe by means of safety analysis or evaluation,
- b) Generate expected errors or safety margin,
- c) Subtract the expected errors of safety margin to obtain the "nominal setting or trip setpoint"



**Fig. 1. Westinghouse RPS Setpoint Generating Scheme**

setpoint" and

d) Add instrument and setpoint drift to the nominal setting in the non-conservative direction to obtain the "limiting safety system setting or Technical Specifications limit".

Fig 1 describes the Westinghouse RPS setpoint generation scheme.

### 3. Safety limit Development

Fuel integrity is both an economic and a safety concern in the operation of a PWR. In recognition of this, the Westinghouse fuel design philosophy is to preclude all but a very limited amount of fuel damage during normal operation and anticipated transients. The fuel design bases established to preclude fuel damages are:

a) A limit is established for the peak LHGR to prevent centerline fuel melting. The uranium dioxide melting temperature shall not be exceeded for at least 95 percent of the limiting fuel rod at a 95 percent confidence level.

b) The minimum DNBR is limited to 1.3 as determined by the W-3 correlation.

c) The hot-leg temperature must be less than the saturation temperature to assure that the vessel average temperature difference ( $\Delta T$ ) is proportional to core power.

The most fundamental element in the safety limit development is to generate DNB limits. It requires an analysis of the dependency of DNBR on system pressure and coolant inlet temperature at various power levels utilizing thermal-hydraulics analysis computer codes such as THINC and COBRA. The pressure-temperature (P-T) analysis produces a set of curves that shows minimum DNBRs as a function of inlet temperature for various system pressures at a given power level as shown in Fig 2. Similar sets of the curves are also generated for different values of reactor power level.

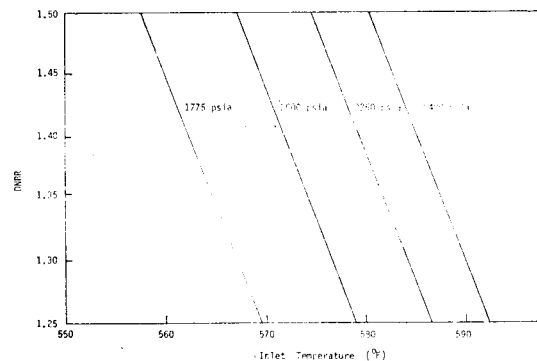


Fig. 2. DNBR vs Inlet Temperature for Various System Pressures at Rated Power

The range of system pressures analyzed includes both the high and low pressure trip setpoints as well as several intermediate pressures. Inlet temperatures are chosen to yield minimum DNBRs that bracket the design minimum DNBR at each pressure plateau. The key assumptions used in calculations are as follows:

a) The axial power distribution is a chopped cosine with a peak to average value ( $F_{\text{ax}}^N$ ) of 1.55.

b) The nuclear enthalpy rise hot channel factor ( $F_{\text{DH}}^N$ ) is 1.55 for power levels of 100% rated or greater, and for power levels less than 100% power  $F_{\text{DH}}^N$  is written as below:  $F_{\text{DH}}^N(\mathbf{P}) = 1.55 [1 + 0.2(1 - \mathbf{P})]$

where  $\mathbf{P}$  is a fractional power.

An  $F_{\text{DH}}^N$  of 1.55 is a typical design value but could be other appropriate value, and the multiplier could also be of different values.

c) The coolant flow rate is the design value which is usually about 5% less than the best estimate flow.

d) The bypass flow is excluded from the available core flow.

e) The coolant flow to the hottest assembly is reduced by 5 percent.

Shown in Fig 3 is a typical set of curves of maximum allowable power level as a function of inlet temperature for various system pressures. These curves are generated through plotting

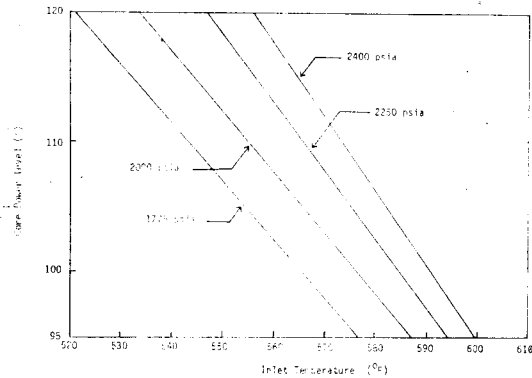


Fig 3. Maximum Allowable Core Power vs Inlet Temperature to Attain Minimum DNBR Limit

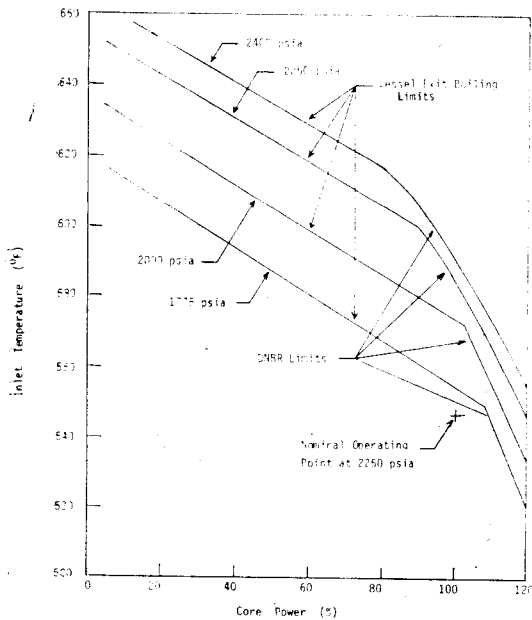


Fig. 4. Typical Core Thermal Limits for a Westinghouse 3-Loop Plant

core power versus inlet temperature corresponding to a minimum design DNBR for different values of system pressure. Such curves of power versus inlet temperature are combined with vessel exit boiling limit and converted to produce final curves of inlet temperature versus core power level. The vessel exit boiling limit is calculated for each pressure based on energy balance within the vessel. Fig 4 shows a set of the safety limits established on the core inlet temperature as a function of core power level

for a Westinghouse 3-loop plant.

#### 4. Development of Thermal Overpower and Overtemperature $\Delta T$ Trip Limits

Reactor trips such as high neutron flux, low coolant flow rate, thermal overpower and overtemperature  $\Delta T$  (OPAT and OTAT) provide core protection against high LHGR and occurrence of DNB in the core. Among these, the former two trips provide core protection for relatively fast transients in which the loop  $\Delta T$  signal does not respond rapidly enough. However, the OPAT and OTAT trips provide complete core protection when

- a) the transient is not fast with respect to piping delays from the core to the temperature sensors, and
- b) the pressure is between the high and low pressure reactor trip setpoints.

Discussed in this section are the thermal overpower and overtemperature  $\Delta T$  trip setpoint development methods, since high neutron flux and low coolant flow rate trip setpoints are determined in a more straight-forward manner.

##### 4.1. Thermal Overpower $\Delta T$ Trip

The thermal overpower  $\Delta T$  trip is specifically designed to provide assurance that the peak LHGR corresponding to the centerline melt will not be exceeded. In OPAT trip, the core thermal power is correlated with the temperature difference across the vessel ( $\Delta T$ ). Since the thermal power is not precisely proportional to  $\Delta T$  because of the effects of changes in coolant density and heat capacity, a compensating term which is a function of vessel average temperature is included in the OPAT trip function. Similarly, since the prescribed overpower limit may not be adequate for highly skewed axial power distributions, another compensating term related to the axial flux difference is included in the OPAT trip function.

The overall approach taken to develop the *OPAT* trip setpoint is as below: add

a) An overpower trip limit is chosen independent of power distribution (typically 118% of the rated power).

b) The power level and the power distribution in the core are evaluated during limiting transients through the use of static nuclear core models (No benefit for plant and core feedback is taken).

c) The limiting LHGR (kw/ft) values in these transients are compared to the values which would lead to fuel centerline melting.

d) If the fuel centerline melting limits are exceeded, an appropriate flux difference trip reset function,  $f(\Delta I)$ , is determined such that highly skewed power distributions leading to high values of LHGR are eliminated.

The  $f(\Delta I)$  is derived based on the " $F_Q$  flyspeck". This flyspeck defines the peak  $F_Q$  (hot channel factor) which is conservatively expected to occur during anticipated transients versus the core axial offset. Fig 5 illustrates how to determine the  $f(\Delta I)$  for the *OPAT* trip based on the  $F_Q$  flyspeck. Solid lines in the

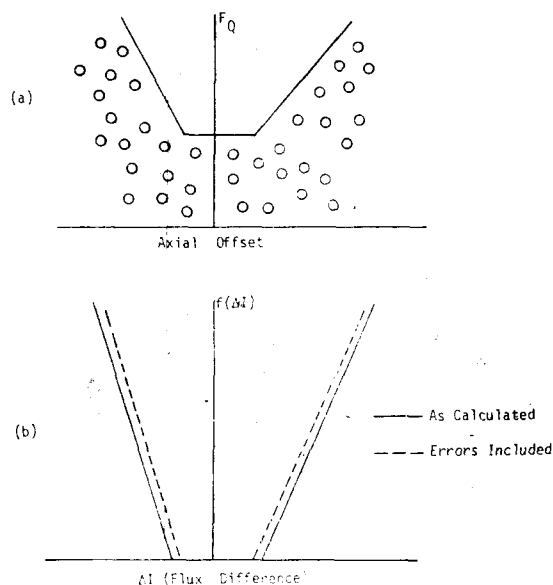


Fig 5. Determination of *OPAT*  $f(\Delta I)$  Function

Fig 5(b) define the calculated values for the  $f(\Delta I)$  function, while dashed lines represent the  $f(\Delta I)$  function with calculation errors taken into account.

#### 4.2. Thermal Overtemperature $\Delta T$ Trip

Since both the DNB design and the hot-leg boiling limits are represented as functions of coolant temperature, pressure and core thermal power, the *OTAT* trip setpoint is also correlated with vessel  $\Delta T$ , vessel average temperature and system pressure. A compensating term as a function of flux difference ( $\Delta I$ ) is also factored into the *OTAT* trip setting to offset the adverse effect of core power distribution on DNB.

The core safety limits illustrated in Fig 4 define a range of safe operation in the space of thermal power level, coolant temperature and coolant pressure assuming the reference core power distribution. To address core power distribution effects on *OTAT* trip, a relationship between power distribution and the axial power imbalance is derived based on a set of standard nonsymmetric axial power distributions as shown in Fig 6. For each power distribution and for a given inlet temperature and pressure, the THINC code is used to determine the power level which will result in a minimum DNBR of 1.30 when the W-3 CHF correlation is used. A bounding curve of such data would have the characteristics sketched in Fig 7. A series of such curves can be generated for several values of coolant temperature and pressure, and the

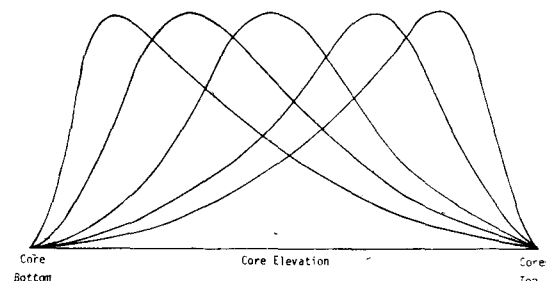
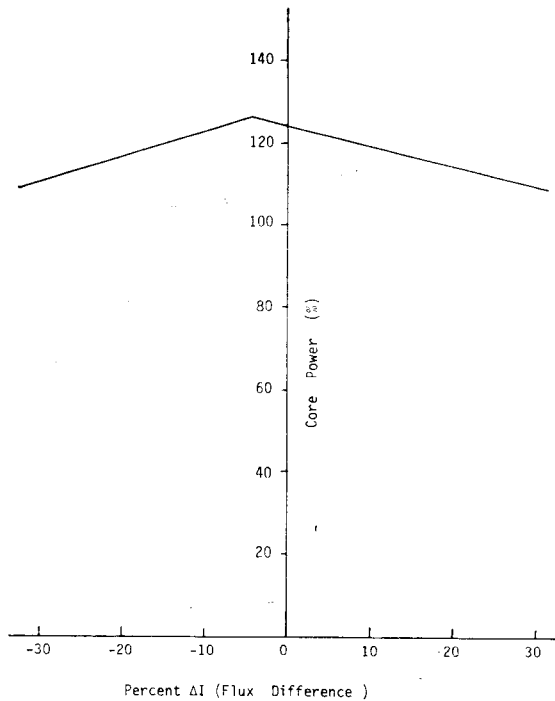


Fig. 6. Axial Core Power Distributions Assumed for Calculation of Axial Position Dependent DNBRs



**Fig 7. Maximum Allowable Power Level vs  $\Delta I$  Corresponding to a DNBR of 1.30**

results can be used to define an  $f(\Delta I)$  correction factor for the *OTAT* setpoint.

**5. LSSS Development**

To generate final LSSS for *OPAT* and *OTAT* trips, the safety limits illustrated in the previous section should be converted into an appropriate form. Also, adjustments should be made to the *OPAT* and *OTAT* trip setpoints allowing appropriate uncertainties.

**5.1. Uncertainty Allowances**

Errors occurring in a RPS trip string must be taken into account in both the determination of trip setpoints and the accident analysis. The RPS trip string errors include sensor, processing equipment and bistable errors. In addition to these errors measurement and/or calibration errors are included in the RPS trip setpoint determination.

The typical error components are listed and

defined as below:

a) Process measurement errors: Errors in measuring the process parameters such as core power, inlet temperature and system pressure. For example, core neutron power measurement error is the error between indicated neutron power from the excore detectors and the heat balance.

b) Calibration errors: Errors involved in the parameter calibration. An example is the core power calibration error due to calorimetric errors in measuring feedwater temperature, steam pressure and moisture carryover.

c) Processing equipment errors: Errors related to equipment calibration and noise.

d) Bistable errors: Maximum difference between the voltage representing the trip parameter and the setpoint reference voltage at the instant the bistable switches to a tripped output. This difference divided by the bistable span in volts equals the setpoint comparison error in unit of % of span.

e) Drift errors: Errors due to the drift of instrument and setpoint.

Of the errors listed above, two errors; process measurement and calibration errors can be categorized as the calibration error, while the processing equipment, bistable and drift errors are categorized as the instrument channel errors.

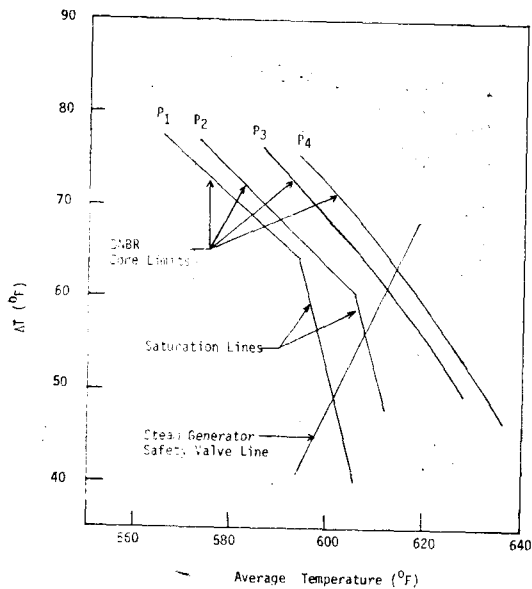
Table 1 presents typical values for estimated and assumed errors considered in the determination of maximum overpower trip point for a typical Westinghouse plant.

**5.2. Setpoint Generation**

Since measured plant variables  $\Delta T$  and  $T_{avg}$  are used in both *OPAT* and *OTAT* trip functions, the core safety limits as shown in Fig 4 are converted into those as shown in Fig 8 where core thermal limits in units of  $\Delta T$  are plotted as a function of  $T_{avg}$  for several system pressures.  $\Delta T$  and outlet temperature are determined based on the values of coolant inlet tem-

**Table 1. Estimated and Assumed Errors Considered in the Determination of Maximum Overpower Trip Point for a Typical Westinghouse Plant**

Type of Error	Estimated Error (%)	Assumed Error (%)
Calorimetric Error (% of Rated Power): Errors Involved in the Measurement of Secondary System Thermal Power	1.55	2
Equipment Error (% of Rated Power): Axial Power Distribution Effects on Total Ion Chamber Current	3	5
Drift Error (% of Rated Power): Instrument and Set-point Drift	1	2
<b>Total Error</b>	<b>5.55</b>	<b>9</b>

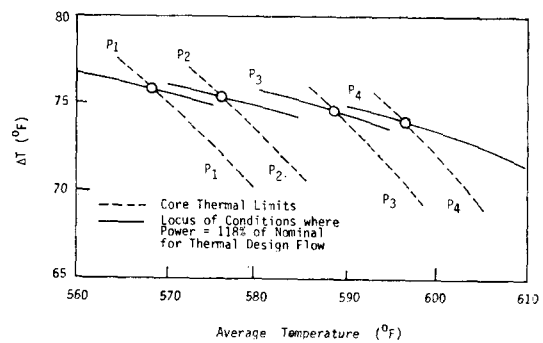


**Fig 8. Typical Core Thermal Limits in  $\Delta T$  vs Coolant Average Temperature**

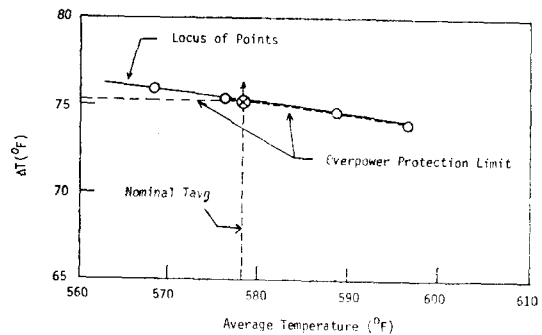
perature, core power level, coolant flow rate and system pressure.

Also, illustrated in Fig 8 is the locus of conditions at which steam generator safety valves open. The steam generator safety valve limit line imposes a physical limit on reactor power and temperature, and is computed from the fundamental log-mean-temperature-difference equation between the primary and secondary side.

The OPAT protection limit equation is determined based on the intersection points of the overpower limit plotted as a function of  $T_{avg}$



**Fig 9. Intersection of Core Thermal Limits and Constant Power at 118% of Nominal**



**Fig 10. Locus of Points for Power at 118% of Nominal and DNBR=1.3 at Full Thermal Design Flow**

for fixed pressures and the DNB core limits at corresponding pressures as shown in Fig 9. The intersections are determined for various pressures ranging from the low pressure trip to the high pressure trip. As illustrated in Fig 9, the  $\Delta T$  at the intersection point decreases as pressure increases. However, there is only a

small dependence on pressure, and the effect of the pressure change can be neglected. The OPAT setpoint equations can be illustrated by the dashed lines on Fig 10, where the point A represents the  $\Delta T$  limit for the reference Tav<sub>g</sub> at rated power and the point B corresponds to the high pressure trip.

Using these approximations, the overpower limit  $\Delta T$  equation may be expressed as:

$$\Delta T_{sp} = \Delta T_o [K_1 - K_3 (T_{avg} - T_{ref})]$$

where

$\Delta T_{sp}$  : setpoint value of  $\Delta T$ ,

$\Delta T_o$  : indicated  $\Delta T$  at nominal plant conditions,

Tav<sub>g</sub>: measured average temperature,

Tref : reference average temperature at rated power,

$K_1$  : preset manually adjusted bias, and

$K_3$  : a constant that compensates for the change in density, flow and heat capacity of water with change in temperature.

Recognizing the protection provided by the overpower  $\Delta T$  trip, DNB safety limit lines, the steam generator safety valve limit line, and the high and low pressure trips, the region which must be protected by the overtemperature  $\Delta T$  trip is bounded. The intersection points, A, B, C and D as shown in Fig 11 provide the basis for calculation of the OTAT equation. The resultant overtemperature  $\Delta T$  protection limit equation is written as:

$$\Delta T_{sp} = \Delta T_o [K_4 - K_5 (T_{avg} - T_{ref}) + K_6 (P - P_{ref})]$$

where

**P** : measured RCS pressure,

Pref : reference RCS pressure at rated power,

$K_4$  : preset manually adjustable bias, and

$K_5$  &  $K_6$  : preset manually adjustable gains.

The constants  $K_4$ ,  $K_5$  and  $K_6$  are decided in a conservative manner utilizing the intersection

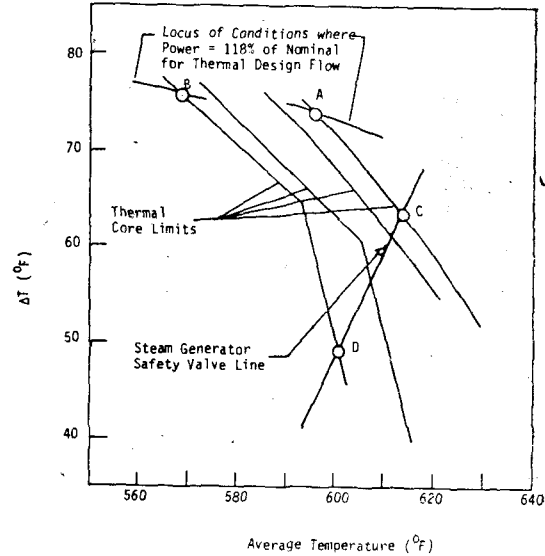


Fig 11. Intersection Points Used to Determine Overtemperature  $\Delta T$  Protection

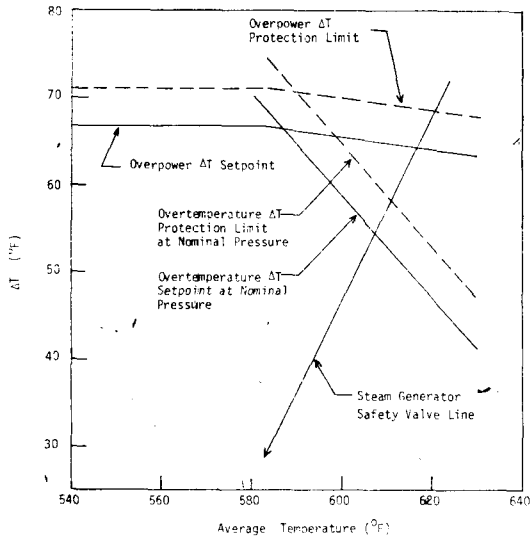
Table 2. OPAT and OTAT Protection Limits, Error Allowance and Final Trip Setpoints for a Typical Westinghouse Plant

Trip	OPAT	OTAT
Protection Limit at Nominal Pressure and Tav <sub>g</sub> , % of Rated Value	115.59	121.58
Error Allowance for Calibration and Instrument Channel Errors, %	7.22	9.57
Final Trip Setpoint, %	108.37	112.01

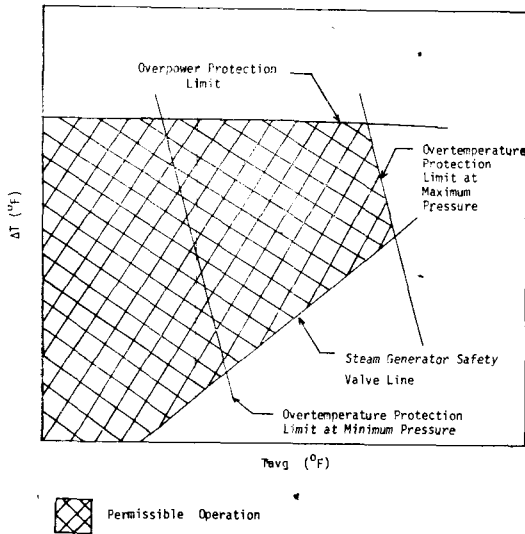
points A, B, C and D in Fig 11.

The above equations represent the maximum allowable overpower and overtemperature  $\Delta T$ 's during operation. However, adjustments should be made to the OPAT and OTAT protection limits allowing appropriate uncertainties including equipment and measurement errors to determine the final  $\Delta T$  setpoints. This is done by adjusting the  $K_1$  term in the OPAT trip function and the  $K_4$  term for the OTAT trip function. Table 2 presents OPAT and OTAT protection limits, final trip setpoints and error allowance for a typical Westinghouse plant. The methodology of obtaining the final OPAT





**Fig 12.  $\Delta T$  Protection Limits vs  $\Delta T$  Setpoints for the Overpower and Overtemperature Trips**



**Fig 13. Region of Permissible Operation as Defined by Core Protection System**

and *OTAT* setpoints is illustrated in Fig 12. The solid lines represent the final *OPAT* and *OTAT* setpoint equations and the locus of conditions where the steam generator safety valves open, while the *OPAT* and *OTAT* protection (safety) limits are represented as dashed lines. The final region of operation, which is defined by the core protection system,

is illustrated in Fig 13.

Now, the effects of core power distribution variations should be included in the development of the *OPAT* and *OTAT* setpoint equations. Such effects are quantified using the  $\Delta T$  trip reset function,  $f(\Delta I)$  as described in the previous section. With the  $f(\Delta I)$  taken into consideration, the final forms of *OPAT* and *OTAT* setpoint static equations are written as:

$$OPAT_{sp} = \Delta T_o [K'_1 - K_3(T_{avg} - T_{ref}) - f_1(\Delta I)], \text{ and}$$

$$OTAT_{sp} = \Delta T_o [K'_4 - K_5(T_{avg} - T_{ref}) + K_6(P - P_{ref}) - f_2(\Delta I)]$$

where  $K'_1$  and  $K'_4$  are error adjusted values of  $K_1$  and  $K_4$ .

Finally, the dynamic terms in *OPAT* and *OTAT* trip equations should compensate for inherent instrument delays and piping lags between the reactor core and the loop temperature sensors. Lead/lag and rate/lag compensations are required in addition to noise filters for the following reasons:

- a) To offset RTD (resistance temperature detector) instrumentation time delays measured during plant startup tests.
- b) To offset piping lags including the RTD bypass-loop transport lag and bypass-pipe heat capacity effects.
- c) To decrease the likelihood of an unnecessary reactor trip following a large load rejection.
- d) To ensure the protection system response is within the limits required for the accident analyses.

The resultant dynamic equations for *OPAT* and *OTAT* setpoints are written as

$$OPAT_{sp} = \Delta T_o [K'_1 - K_2 \left( \frac{\mathcal{F}_2 S}{1 + \mathcal{F}_2 S} \right) T_{avg} - K_3(T_{avg} - T_{ref}) - f_1(\Delta I)],$$

and

$$OTAT_{sp} = \Delta T_o [K'_4 - K_5 \left( \frac{1 + \mathcal{F}_4 S}{1 + \mathcal{F}_5 S} \right) (T_{avg} - T_{ref}) + K_6(P - P_{ref}) - f_2(\Delta I)],$$

where

- $K_2$  : a constant that compensates for piping and thermal time delays,
- $\mathcal{T}_2, \mathcal{T}_4, \mathcal{T}_5$  : time constants (seconds),
- $S$  : Laplace transform operator (seconds<sup>-1</sup>).

Written below is an example of the *OPAT* and *OTAT* setpoint equations for a typical Westinghouse Plant (refer to Table 2):

$$OPAT_{sp} = \Delta T_o \left[ 1.0837 - 0.0275 \frac{10S}{1+10S} \right. \\ \left. T_{avg} - 0.00112 (T_{avg} - 582) - f_1(\Delta I) \right], \text{ and}$$

$$OTAT_{sp} = \Delta T_o \left[ 1.1201 - 0.0095 \frac{1+30S}{1+2S} \right. \\ \left. (T_{avg} - 582) + 0.000672 (P - 2235) - f_2(\Delta I) \right].$$

### 6. Conclusion

Reviewed are Westinghouse RPS setpoint generation philosophy, methodology of safety limit development and trip setpoint generation procedure.

The Westinghouse RPS trip setpoint generation methodology has been established based on the selection of core safety limits and LSSS allowing appropriate uncertainties in a conservative manner, and assures a high degree of core protection against fuel melting and occurrence of DNB. Among various reactor trips, *OPAT* and *OTAT* trips provide complete core protection when the transient is not fast with respect to piping delays from the core to the temperature sensors.

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