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BEST ESTIMATE FRAP-T4 ANALYSES OF SELECTED POWER REACTOR TRANSIENTS AND ACCIDENTS

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ABSTRACT

The fuel performance characteristics of several power reactor operating transients are evaluated based on best estimate FRAP-T4 calculations. Results of lead rod analyses are discussed for locked rotor, control element ejection, steam line break, loss of flow, and turbine trip events. The propensity for fuel damage to occur during such events is expressed relative to various threshold and cumulative damage criteria. Model development, support analysis, uncertainty study and data analysis needs are identified.

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SUMMARY

NRC is interested in improving both analytical and experimental bases for characterizing LWR fuel performance during non-LOCA operating transients and accident situations. Best estimate application of the FRAP-T4 code to these conditions provides analytical input to a process by which current fuel damage criteria can be evaluated or alternate criteria developed. The objective is to arrive at a more realistic understanding of fuel damage thresholds, fuel failure consequences and contributing operating conditions. In so doing, the acceptance criteria applied for fuel damage, failure, and coolability can be related to the various reactor conditions considered in licensing analyses.

FRAP-T4 was used to calculate various fuel damage related parameters for five generic transients, namely, locked rotor, rod ejection, steam line break, loss of flow, and turbine trip events. Best estimate modeling options were used in all cases. Initial conditions corresponded to lead rod operation at beginning of life. System condition and power histories were vendor supplied.

Analytical results were compared with currently used or proposed fuel damage parameters and licensing predictions. Uncertainties were applied to FRAP-T4 results based on independent code assessments and the state of model development. The fuel damage potential was evaluated for each transient. The individual runs and generic transients that are candidates for subsequent experimental or analytical emphasis are identified based on the calculation of integral damage indices. Conclusions are reached regarding transient fuel performance analysis requirements for model development and supporting analyses, uncertainty studies and data analysis.

I. INTRODUCTION

The Core Performance Branch of NRC's Division of Systems Safety has funded a technical assistance program to analyze LWR fuel performance during various operating transients and accident situations. The overall purpose of the program is to provide a more realistic understanding of fuel duty, particularly under conditions where current nonmechanistic licensing criteria are applied. As a result, more accurate evaluations can be made of the fuel failure mechanisms that impact core response during postulated transient and accident operation.

The fuel system design of a nuclear power plant is evaluated by the Core Performance Branch. The evaluation provides assurance that the reactor core will function under anticipated transient and accident conditions without exceeding certain fuel damage limits. These limits are established in the Code of Federal Regulations[1], in NRC's Standard Review Plan[2], and in the Safety Analysis Reports[3-6], submitted in support of operating license applications. In general, the absence of fuel rod failures during anticipated operation, the assessment of fuel failures under accident conditions, and the maintenance of both shutdown capability and a coolable core configuration must be demonstrated.

Fuel damage limits are most commonly referred to in chapters 4 and 15 of safety analysis reports (SAR's). The applicant places generally accepted constraints on allowable cladding temperature, deformation, and oxidation, fuel temperature and energy content, and rod internal pressure. Conservative results of computerized fuel behavior models are used to evaluate whether damage criteria are met and whether failure consequences meet system condition and radioactive release limits. Applicable operating experience and integral experimental data are usually not available under anticipated transient and accident

conditions. As a result, NRC's review of the fuel system design requires use of some independently developed analytical capability. This capability should keep pace with the state of the art of both applicant methodology and the growing understanding of fuel behavior research results in the nuclear community. In short, to quantitatively audit integral results of conservative reactor safety calculations, it is necessary to analytically characterize the best estimate response distribution for various fuel performance limits.

The RSR sponsored fuel rod models, FRAPCON[7] and FRAP-T[8] can provide up to date fuel behavior analyses of steady state and transient reactor operating conditions. Both modeling deficiencies and best estimate predictive capabilities are demonstrated in the course of an independent verification procedure[9-11]. In anticipation of various fuel damage criteria being used by both applicants and the regulatory agency in their interpretation of transient and accident analyses in Chapter 15, FRAP-T has been used to analyze different aspects of fuel duty for selected transients. FRAP-T4 calculated fuel performance parameters are reported here in an effort to support or refine currently applied nonmechanistic fuel damage limits, such as the departure from nucleate boiling ratio (DNBR). Development of realistic fuel damage criteria is a positive response to the problem of insuring adequate safety margins without introducing unneccessary conservatism in the process.

Section II briefly describes the FRAP-T code. Sections III and IV identify the transients analyzed and the best estimate modeling options used. Section V describes various fuel damage parameters used to represent limiting performance thresholds in both physical and operational terms. Section VI presents integral fuel damage evaluations for each transient according to two different damage accumulation methods. Recommendations and references are given in Sections VII and VIII.

II. CODE DESCRIPTION

FRAP-T4 is intended to predict the transient behavior of fuel rods following perturbations from normal operation such as those caused by a loss-of-coolant accident (LOCA), a power-coolant-mismatch (PCM), or a reactivity initiated accident (RIA). Documentation pertaining to the present models is given in three separate volumes. Reference 8 documents FRAP-T4 models, input format, and other running instructions. Reference 12 describes the fuel rod material property package, MATPRO. Reference 9 presents the results of independent FRAP-T4 model verification studies.

In summary, the FRAP-T4 program is capable of calculating fuel rod transient temperature and deformation responses, brought about by rapid changes in rod power level or cladding surface boundary conditions. The transient conduction equation is solved at input or internally specified time intervals. Changes in material properties, pellet, gap, and cladding surface heat transfer conditions, rod internal pressure distribution, mechanical interaction state, and rod deformation are taken into account. The current structural analysis computes both fuel and cladding deformation occuring as a result of thermal expansion, hydrostatic pressure differences, gap closure, and high-temperature cladding rupture. Output from the mechanical response model interacts with material properties and transient thermal models because individual node displacement, temperature, and rod internal pressure must all satisfy convergence criteria for the calculation to proceed. Features of the code such as gas flow, oxidation, ballooning, melt volume, and failure analysis models are intended to facilitate its application to fuel behavior problems having significance in reactor safety analysis.

Development activity has resulted in an interactive framework of modular subroutines which fulfills thermal-mechanical feedback requirements for off-normal fuel behavior analyses. Constituent FRAP-T4 models are not all in final versions, but the overall code structure

is considered firm for single rod applications. Rod geometry and design parameters, equivalent channel dimensions, inlet fluid conditions, power history, nodalization, convergence criteria, time steps, and various option flags are the minimum user input requirements. If necessary, thermal-hydraulic boundary conditions, time and location of CHF, and correlation multipliers can be user-supplied based on results of experiments or supporting analyses. The code is dimensioned to handle rod arrays of limited size, but currently no internal feedback is provided to account for rod-to-rod interactions occurring as a result of flow redistribution, cladding deformation, or fuel failure.

III. RUN IDENTIFICATION

Five generic operating transients were analyzed with FRAP-T4 [a], as indicated by the left hand column of Table I. System condition and normalized power histories were supplied by the participating vendors as shown. The ten cases considered are each identified by the given run ID. The fuel design data are representative of different assembly configurations, as also shown. The fuel design parameters were consistent with those reported in the Reference Safety Analysis Report for each vendor [3-6]. Initial conditions in all cases corresponded to beginning of life operation of the lead rod at the core design overpower heat rating. Characteristics and duration of the transient operating history are indicated on Table I for each run. Maximum transient deviations from initial channel power, flow, coolant pressure and inlet temperature conditions are listed in normalized units. These deviations were vendor supplied and do not necessarily represent "worst case" conditions.

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[a] FRAP-T, MOD-004, Version May 2, 1978, MATPRO-10, Configuration Control No. H00372IB.

TABLE I

IDENTIFICATION OF FRAP-T4 OPERATING TRANSIENT ANALYSES

	B&W	CE	W	GE
Locked Rotor	**B&W**	**CE**	**W**	**GE**
Run ID	LR-1		LR-2	
Fuel design	17x17		17x17	
Characteristics*	A, B		A	
Duration (sec)	6.095		9.95	
Max ALHR(t)/ALHR(0)	1.05		1.00	
Min Flow(t)/Flow (0)	0.76		0.64	
Max Press(t)/Press(0)	1.0		1.00	
Max $h_{in}(t)/h_{in}(0)^{\Delta}$	1.0		1.00	
Rod Ejection	**B&W**	**CE**	**W**	**GE**
Run ID	RE-1	RE-2	RE-3	
Fuel design	17x17	16x16	17x17	
Characteristics	B, C	B	B	
Duration (sec)	5.0	4.8	9.90	
Max ALHR(t)/ALHR(0)	5.30	1.78	1.55	
Min Flow(t)/Flow(0)	1.00	1.00	1.00	
Max Press(t)/Press(0)	1.14	1.00	1.00	
Max $h_{in}(t)/h_{in}(0)$	1.00	1.00	1.00	
Steam Line Break	**B&W**	**CE**	**W**	**GE**
Run ID	SLB-1			
Fuel design	15x15			
Characteristic	A, B, C			
Duration (sec)	10.0			
Max ALHR(t)/ALHR(0)	1.006			
Min Flow(t)/Flow(0)	0.46			
Min Press(t)/Press(0)	0.69			
Max $h_{in}(t)/h_{in}(0)$	0.94			
Loss of Flow	**B&W**	**CE**	**W**	**GE**
Run ID		LOF-1	(UC)LOF-2(NC)°	
Fuel design		16x16	17x17	
Characteristics		A, B	A, B, C, - A	
Duration (sec)		6.0	30.0 - 9.95	
Max ALHR(t)/ALHR(0)		1.01	1.01 - 1.00	
Min Flow(t)/Flow(0)		0.71	0.10 - 0.56	
Max Press(t)/Press(0)		1.00	1.14 - 1.00	
Max $h_{in}(t)/h_{in}(0)$		1.00	1.0 - 1.00	
Turbine Trip w/o Bypass	**B&W**	**CE**	**W**	**GE**
Run ID				TT-1
Fuel design				8x8
Characteristics				A,B,C
Duration (sec)				10.0
Max ALHR(t)/ALHR(0)				2.60
Min Flow(t)/Flow(t)				0.51
Max Press(t)/Press(0)				1.14
Max $h_{in}(t)/h_{in}(0)$				1.01

*A = Flow decrease
B = Power increase
C = Pressure increase or decrease

°uc = ultra conservative
nc = normal coastdown
$^{\Delta}h_{in}$ = Coolant inlet enthalpy

IV. MODELING CONVENTIONS

With the exception of using each vendor's CHF correlation, consistent modeling conventions were applied to all runs. Some modeling conventions were functional in nature and were decided on from the standpoint of practicality and input limitations. Radial nodalization consisted of 10 fuel intervals, one gap interval and two cladding intervals. Axially, the rods were divided into 15 equal intervals. FRAP-T4's equivalent closed channel fluid analysis was used with the steady state enthalpy rise calculated internally based on inlet conditions. The relatively flat radial power distributions used were based on the FRAPCON model[7] for low enrichment commercial rods. Initial condition axial power distributions were held constant throughout the transients. Relatively loose convergence criteria (0.1) were specified for the temperature and pressure iterations. Azimuthal temperature distributions were not calculated. The transient plenum temperature model was turned on. No decay heat was added to the vendor supplied power histories. Between 60 and 120 time steps were used to represent the transients.

Other modeling conventions were based on the need to generate best estimate results. Independent verification results[9,10,13,15] supported the use of fuel relocation, effective pellet conductivity, and Ross-Stoute gap conductance in the thermal model. The Cathcart cladding oxidation model was used instead of the Baker-Just Model[8]. CHF correlations[8,9] were those based on the data of the respective vendors, B&W-2, W3, CE-1, and GE. The non-uniform axial power factors were applied to the CHF correlations, but not the cold wall factors. The Groeneveld 5.9 film boiling correlation was used to model post-CHF surface heat transfer, based on relatively good agreement with corrected PBF cladding temperature measurements[16]. The FRACAS-I mechanical response model was used instead of FRACAS-II because of its more realistic relocation coupling[9,14] with thermal conductivity calculations and stress-dependent failure probability models in FRAIL[18].

V. FUEL DAMAGE PARAMETERS

Safety analysis reports [3-6] and NRC positions [2,17] were reviewed in an effort to define a base-line set of parameters by which to evaluate fuel damage in the current study. Table II summarizes results of this survey in terms of parameters calculated by FRAP-T4. The various fuel damage parameters and performance limits most often applied for safety evaluation purposes have been listed. The "prevent condition" refers to undesirable consequences which are assumed to be avoided if the corresponding fuel performance limit is not exceeded during reactor operation.

The fuel damage parameters fall into two categories: 1.) fuel operating condition indices such as DNBR, fuel enthalpy and internal pressure and 2.) fuel physical condition indices such as fuel and cladding temperature, cladding oxidation, stress, and strain.

The fuel operating condition criteria do not in themselves provide mechanistic descriptions of the primary fuel damage effect to be avoided such as the extent of clad overheating or oxidation. Operating conditions can, however, be associated with more or less incidence of integral fuel damage based on the behavior observed in representative experiments.

The fuel physical condition criteria can provide more basic descriptions of the thermal, mechanical, and chemical effects that may all contribute to the integral fuel damage potential in different situations. Physical conditions can more easily be associated with material property limitations of fuel rod components and the mechanistic consequences of exceeding them.

VI. ANALYTICAL RESULTS

The presentation of FRAP-T4 results in the present study is based on the comparison of predictions with various fuel damage parameters. Some currently used parameter limits were previously listed in

TABLE II

CURRENTLY USED* BOL FUEL DAMAGE PARAMETERS

PARAMETER	PREVENT CONDITION	LIMIT
Surface heat flux	PWR rod temperature increase	1.3 DNBR
	BWR rod temperature increase	1.0 MICHFR
T_{clad}	α-β phase transition	1500-1900F
	Oxidation threshold	1800F
	Prohibitive oxidation/loss of mechanical strength	2200F
	Embrittlement/fragmentation	2700F
	Clad melting	3300F
T_{fuel}	Incipient fuel melting	5080F
	Potential molten fuel-clad contact	10% melt vol
Fuel Enthalpy	BWR clad failure threshold	170 avg cal/gr
	PWR clad failure threshold	200 "
	Clad oxidation threshold	210 "
	Molten fuel presence	260 "
	Clad fragmentation/fuel dispersal/pressure pulses	280 "
Clad Oxidation	Excessive embrittlement effects	17% thickness
Clad Stress	Exceeding ultimate strength	$f(T_{clad})$
Clad Strain	Hard PCI	1%
Internal Pressure	Tensile stress/ballooning	system pressure

* As either accepted by NRC or submitted by vendors.

Table II. Other parameters were considered for which damage limits are as yet uncharacterized (eg. time in DNB, film boiling length, stress dependent cladding failure probability, time at temperature). Predictions have been summarized in Table III. The DNB ratios are the minimums calculated during each transient. Results for all of the other damage parameters correspond to maximum values.

Figures 1 through 7 summarize for each fuel damage parameter in Table II the comparison between FRAP-T4 results and the damage limit of interest. Representative results from reference Safety Analysis Reports have been indicated on the figures when available. Vertical bars correspond to the assumed effects of FRAP-T4 model uncertainties. These effects are consistent with the results of independent code assessment activities.

Figure 1 shows that for the given set of input conditions, current DNBR limits are met by 3 runs, LR-1, SLB-1, and TT-1. DNBR results are quite dependent on the vendor-supplied power and system histories, however, which may not all reflect the same calculational assumptions or philosophy. In any event, FRAP-T4 calculations should be conservative in this area, as indicated by the non-uniform uncertainty bars. Conservative tendencies are the result of the code's closed channel, steady state thermal-hydraulic model. This contention is supported by general consistency between the FRAP-T4 calculated DNBR and the indicated results of normally conservative safety analyses. FRAP-T4 either predicts film boiling (DNBR $\leq$ 1.0) or is close to it for half of the runs, LR-2, RE-1, RE-2, RE-3 and LOF-2 (UC)[a]. With respect to run LOF-2 (NC)[b], the results of run LOF-2 (UC) show that significant DNBR margin is eliminated when a conservative flow condition (in this case, pump coastdown) is used.

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[a] ultra-conservative pump coastdown

[b] normal pump coastdown

TABLE III

SUMMARY FRAP-T4 RESULTS FOR SELECTED POWER REACTOR OPERATING TRANSIENTS

Run ID	min DNBR (frac)	Time in DNB (sec)	max σ_{cr} (psi)	max T clad (^oF)	film boiling length (%)	max ε_{cr} (im/im)	max % oxide	max gap press. (psia)	max fuel temp (^oF)	max stored energy(cal/g)	max P_{fail}*** (frac)	$\int_{Tb}(T(t)-T(nb)dt$ (F-s)
LR-1	1.416	-	-9753.	659.0	0.0	1.652 E-3	0.042	1132.	4260.6	109.4	0.0	0.0
node #	12		1-8	8		8	1-15	1-15	8	8		
LR-2	<1.0	4.7	-7271.	1198.1	6.67	3.572 E-3	0.043	1526.	3660.6	84.1	0.0	1448
node #	13	13	3-8	10		10	1-15	1-15	8	8		13
RE-1	1.020	-	-9553.	678.7	0.0	1.820 E-3	0.042	1269.	4820.4	137.6	0.0	0.0
node #	11		1-8	8		8	1-15	1-15	8	8		
RE-2	<1.0	2.12, 1.92	-3071.	1077.9	13.3	3.626 E-3	0.039	2126.	4144.9	102.8	0.0	680
node #	13, 14	13, 14	15	13		13	1-15	1-15	10	10		13
RE-3	<1.0	3.6	+ 19,090.	1212.8	40.0	4.474 E-3	0.043	1759.	4376.1	110.3	0.0345	1300
node #	9-14	13	9	10		9	1-15	1-15	8	8		13
SLB-1	1.419	-	+ 62,670.	658.6	0.0	1.026 E-2	0.037	2062.	4896.4	147.2	0.65	0.0
node #	13		6	8		8	1-15	1-15	8	8		
LOF-1	1.296	-	+ 17,630.	670.9	0.0	3.835 E-3	0.039	1747	4496.8	110.0	0.0	0.0
node #	4		2	2		2	1-15	1-15	2	2		
LOF-2(UC)*	<1.0	26	11,920.	1577.0	60.0	-2.693 E-2	0.288	1932	4382.6	114.9	0.00379	14200
node #	7-15	11	9	8		9	8	1-15	8	8		8
LOF-2 (NC)**	1.262	-	-4242.	658.5	0.0	2.078 E-3	0.044	1927	4381.6	114.8	0.0	0.0
node #	13		1-15	8		8	1-15	1-15	8	8		
TT-1	2.416		-7590.0	589.1	0.0	1.407 E-3	0.0296	65.93	2896.6	81.1	0.0	0.0
node #	15		1-15	15		6, 7, 8	1-15	1-15	6	6		

* ultra conservative

** normal coastdown

*** stress-dependent cladding failure probability[18]

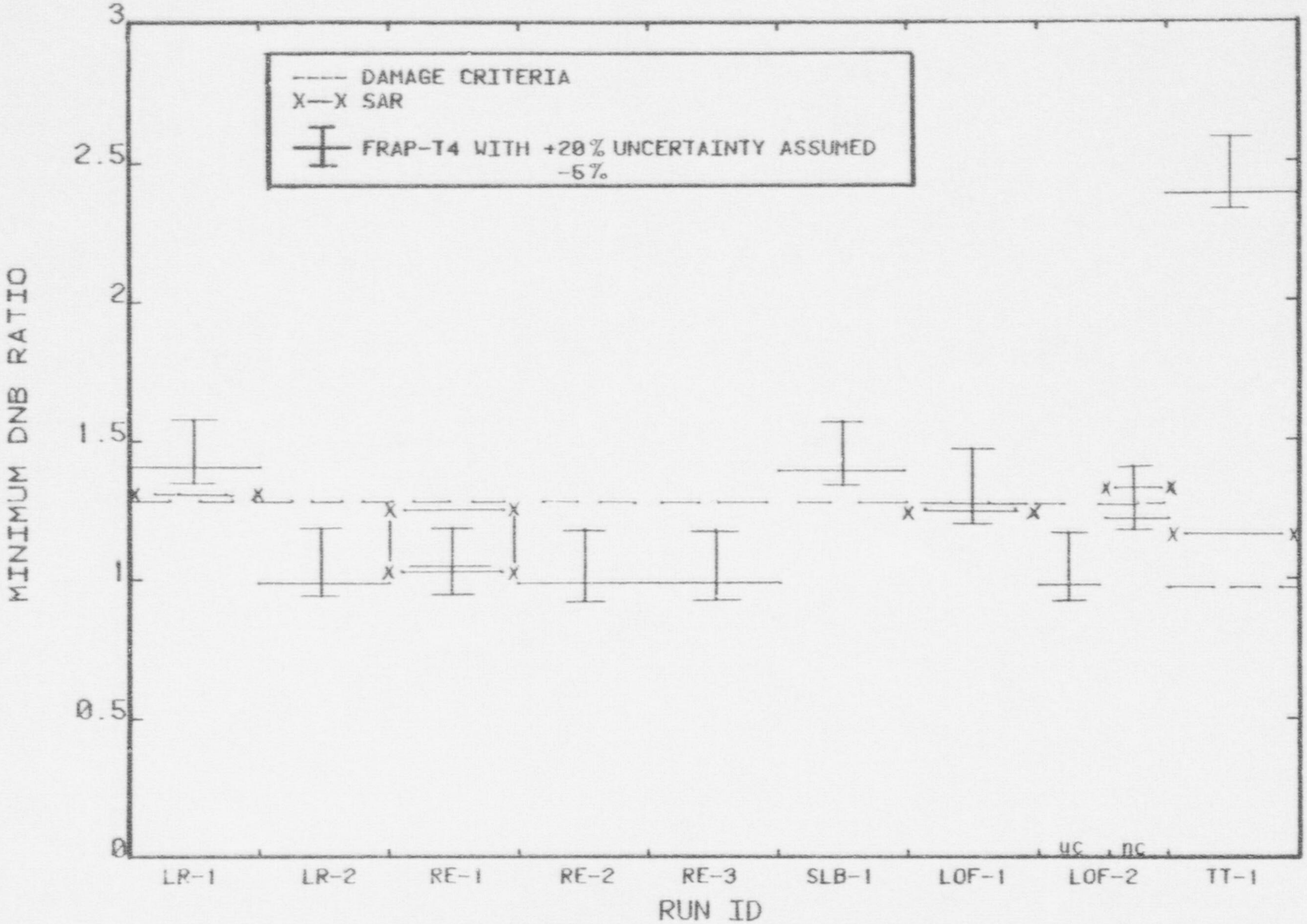

Fig. 1 Comparison between FRAP-T4 calculated minimum DNBR and 1.3/1.0 DNBR criteria.

The uncertainty in FRAP-T4 cladding temperature predictions, shown in Figure 2, reflects uncertainty in whether or not DNB occurs and as much as 300^{o}F possible error in the film boiling temperature increase [16]. Only for the conservative loss of flow event, LOF-2 (UC), is a potential for cladding oxidation predicted. For two additional runs, LR-2 and RE-3, cladding material properties should be subject to large uncertainties due to the possibility of α - β phase transition. Despite close agreement between FRAP-T4 and SAR DNBR results, FRAP-T4 cladding temperatures are much lower than the licensing analyses. In addition to possible differences between the current FRAP-T4 input and that used in SAR analyses, SAR analyses tend to specify that if film boiling occurs, it does so early in the transient when fuel stored energy is highest. Also, conservative vendor analyses use the Baker-Just correlation to account for additional cladding heat input due to oxidation.

Whether or not FRAP-T4 cladding stress conditions meet the ultimate strength criteria shown in Figure 3, depends on the influence of DNB and PCI (pellet cladding interaction). It is assumed that DNB potential lowers the normally high (>50 Ksi) cladding strength range based on temperature dependent failure stress properties used in FRAIL development [18]. The fact that pellet relocation does not contribute to mechanical gap closure in FRACAS-I causes a +20 Ksi tensile stress uncertainty. A negative stress uncertainty, which totally relaxes PCI contact pressure, has been applied to the hard gap closure cases, RE-3, SLB-1, LOF-1, and LOF-2 (UC). Mechanical cladding damage potential exists in half of the runs considered; namely, LR-2, RE-2, RE-3, SLB-1, and LOF-2 (UC). Chemically assisted (SCC) mechanisms may increase damage potential under burnup conditions [14].

Maximum cladding hoop strain is compared with $\pm$1% criteria in Figure 4. The positive strain criterion corresponds to hard gap closure (PCI) conditions. The negative strain criterion reflects cladding collapse to the point at which subsequent fuel expansion may induce hard gap closure. FRAP-T4 strains approach +1% limits for the 4 runs

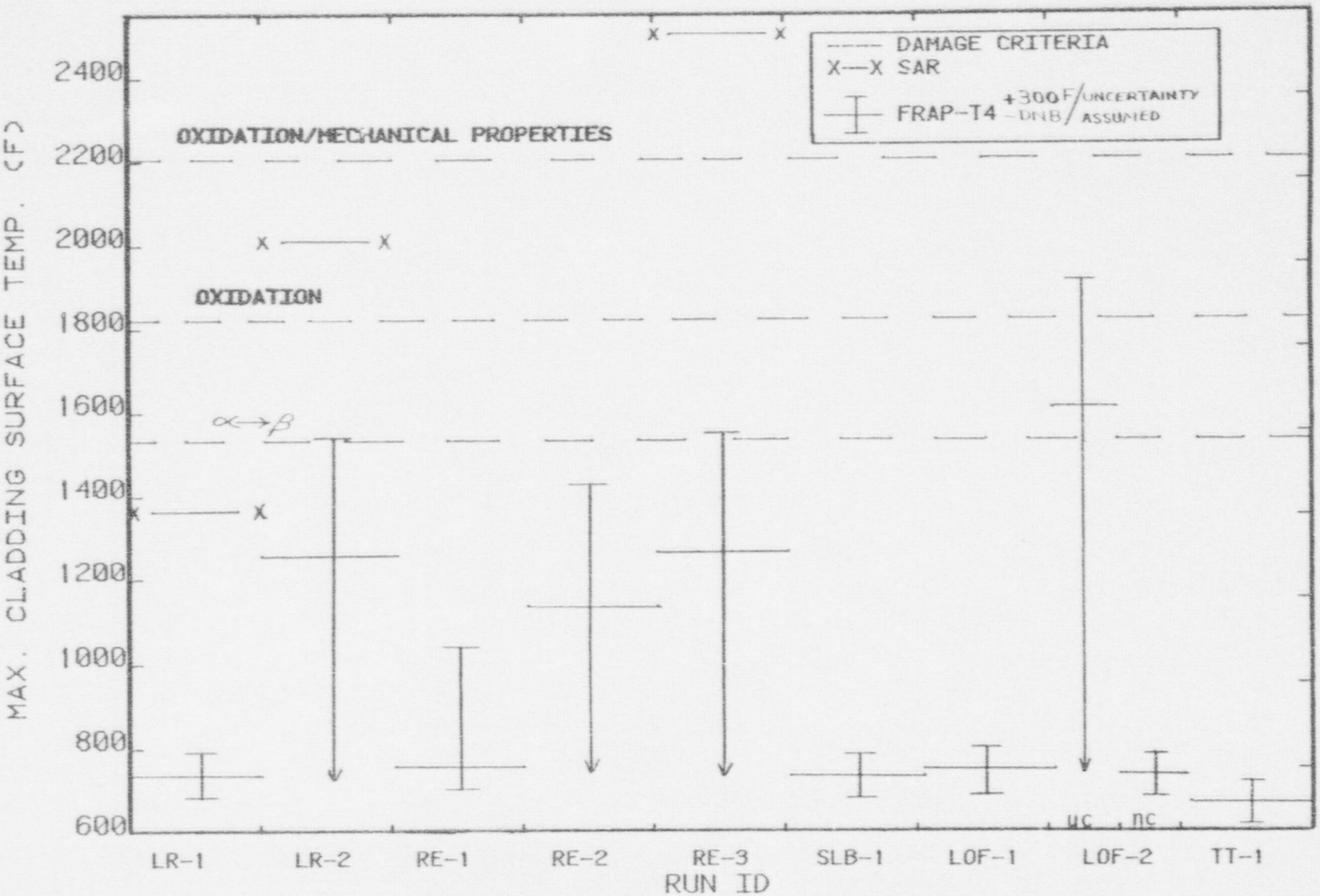

Fig. 2 Comparison between FRAP-T4 calculated maximum clad surface temperature and material properties/oxidation criteria

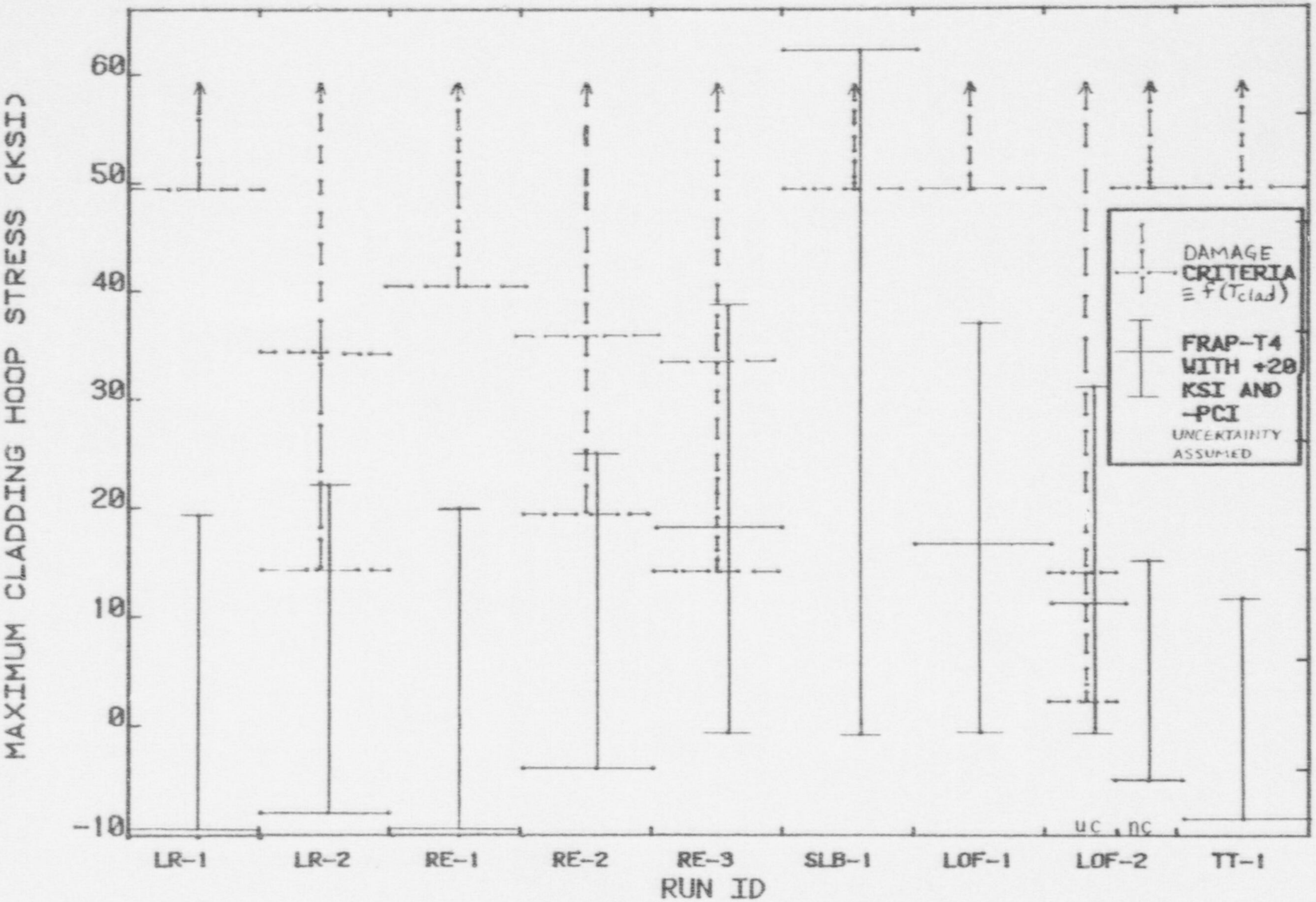

Fig. 3 Comparison between FRAP-T4 calculated maximum clad hoop stress and clad ulitmate strength criteria.

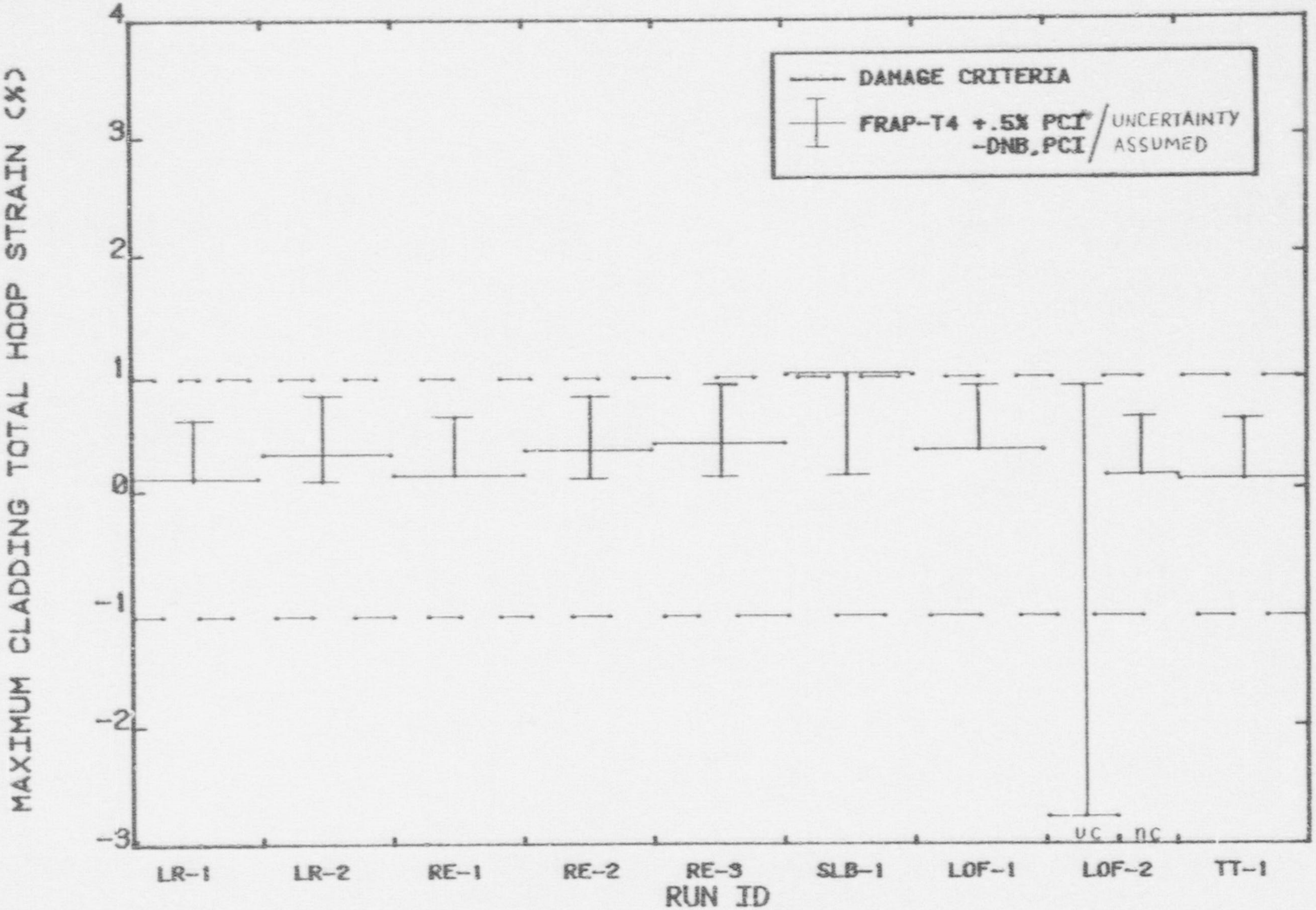

Fig. 4 Comparison between FRAP-T4 calculated maximum cladding hoop strain and ±1% strain criteria.

(RE-3, SLB-1, LOF-1, and LOF-2 (UC)), previously shown in Figure 3 to have the most PCI potential. Removing both a.) temperature effects of DNB on clad thermal expansion and/or collapse, and b.) PCI effects, contributes to negative uncertainty in calculated strain. The influence of uncertainty in whether DNB occurs is largest for Run LOF-2 (UC), since relatively high cladding temperatures led to collapse being predicted.

FRAP-T4 predictions shown in Figure 5 coincide with system condition limits on rod internal pressure for 2 runs, RE-2 and SLB-1. The non-uniform model uncertainties reflect the tendency of FRAP-T4's relocated void volume and temperature model to overpredict steady state FRAP-S3 pressure levels, shown by verification[9,10] to be best estimate values. FRAP-T4 results for the BWR rod show the largest difference with system conditions, as expected. High burnup results for RE-3, LOF-1, and LOF-2 may approach system conditions if the cumulative (steady state and transient) gas release fraction exceeded a few percent.

Comparisons between FRAP-T4 fuel temperature and stored energy conditions and associated thermal and mechanical damage criteria are shown in Figures 6 and 7. Center temperature results for runs RE-1 and SLB-1 approach the BOL limit for incipient melting in Figure 6. The same 2 runs yield maximum stored energies in Figure 7 without violating the non-mechanistic cal/g limits. Consistent with clad temperature results in Figure 2, fuel thermal conditions predicted by conservative SAR models are again significantly more severe than the current FRAP-T4 results in both Figures 6 and 7.

Certain FRAP-T4 output parameters in Table III were not graphically compared with fuel damage criteria. The maximum cladding thickness fraction that underwent oxidation (0.29%) was well below the 17% embrittlement criterion. This fact can be attributed to the maximum cladding surface temperature being less than 1600°F for the nominal result. Relative fuel damage based on time in DNB, film boiling

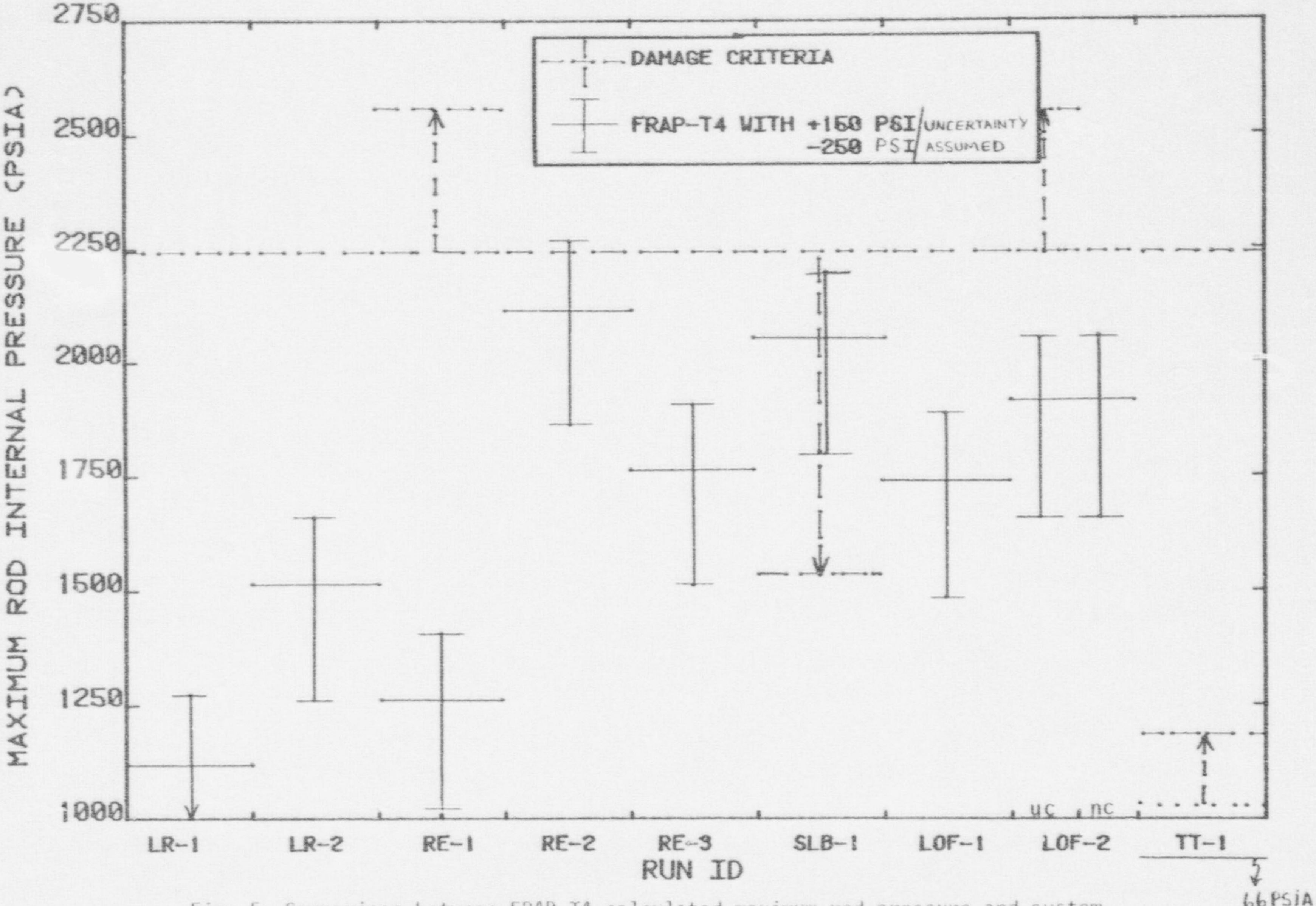

Fig. 5 Comparison between FRAP-T4 calculated maximum rod pressure and system pressure criteria.

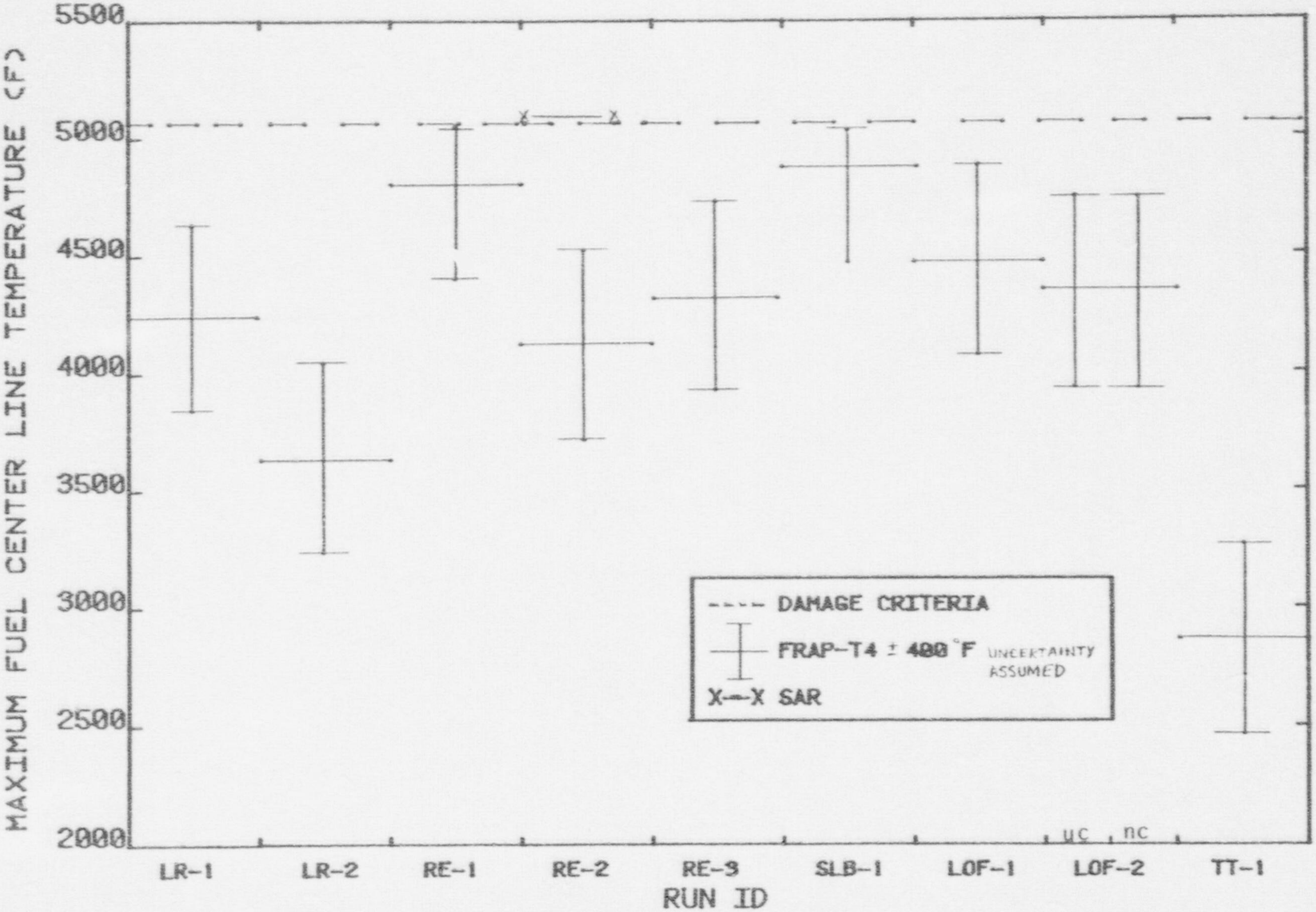

Fig. 6 Comparison between FRAP-T4 calculated maximum centerline temperature and incipient fuel melting threshold.

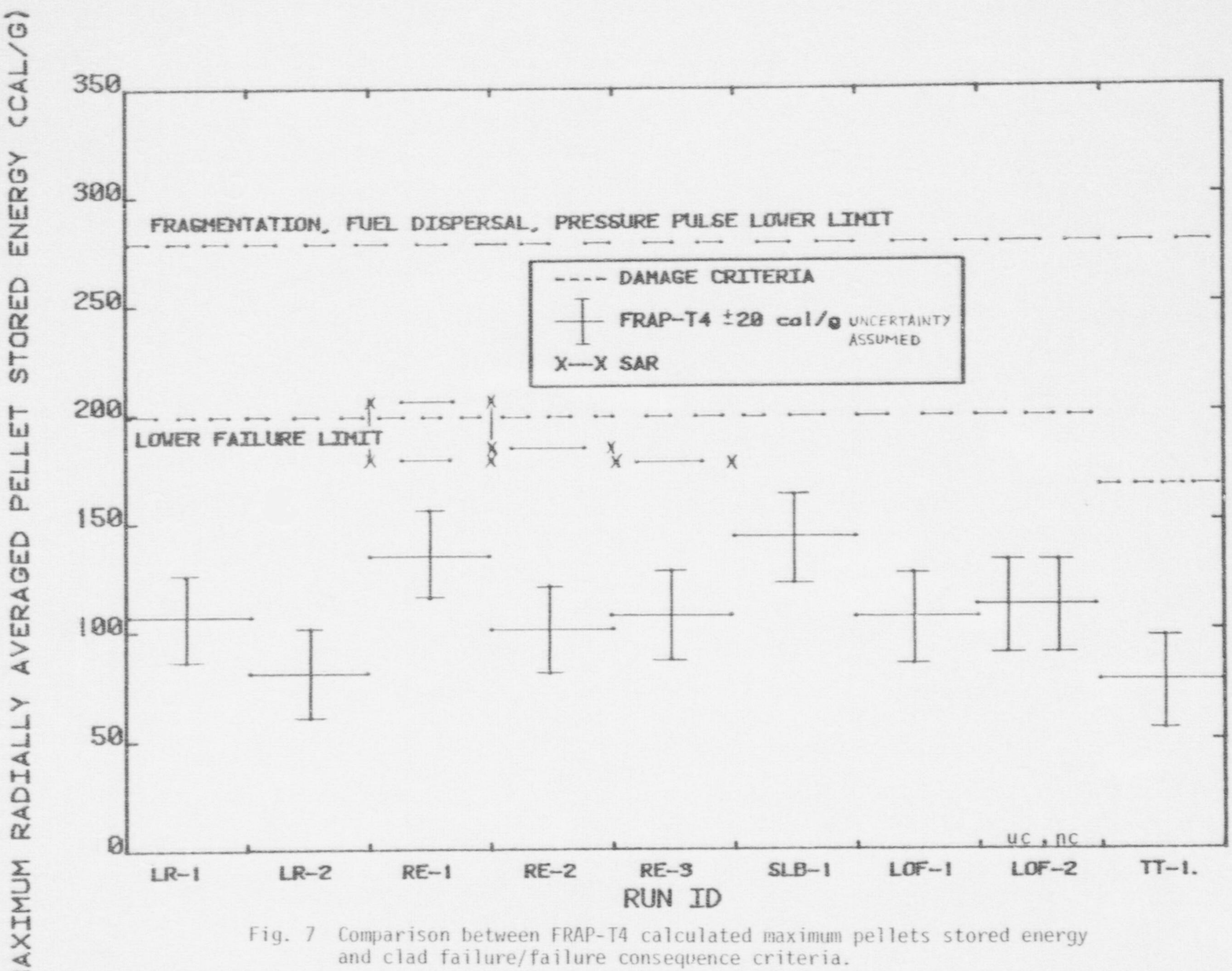

Fig. 7 Comparison between FRAP-T4 calculated maximum pellets stored energy and clad failure/failure consequence criteria.

length, and integral time at temperature results are all consistent with cladding temperature trends previously shown in Figure 2; relative cladding failure probabilities based on ultimate strength at temperature relationships in FRAIL, are consistent with cladding stress conditions shown in Figure 3. Only qualitative results can now be inferred from the four alternate damage parameters considered. Data availability and analysis have not progressed to the point where new damage limits can be established with high enough confidence for use in safety evaluations.

Individual runs or generic transients that are potential candidates for sensitivity analyses, can be identified by ranking the relative accumulation of fuel damage calculated for the 10 runs being considered. Fuel damage is expressed here in two different ways, a.) a fuel damage value of 0 or 1 is assigned, based on whether specific criteria shown graphically in Figures 1 through 7 are met or exceeded, and b.) each parameter in Table III is assigned a fuel damage value in order of increasing severity from 1 to 10. A cumulative damage index for each run or generic type of transient results from summing the damage values over all the damage parameters. The graphical results of methods (a) and (b) are shown respectively in Figures 8 and 9. The fact that consistent trends in the cummulative damage index occur for both method (a) and (b) is significant. Individual run and generic priorities for analytical and experimental work can be technically supported based on either accepted or proposed criteria or both. The relative amounts of fuel damage calculated by FRAP-T4 for runs in the current study are summarized in Table IV. Assuming that FRAP-T4 modeling deficiencies have either been accounted for, or introduce similar errors in all runs, allows the relative damage ranking to be made with some confidence. Again, it shoud be noted however that conditions and assumptions reflected in the given power and system histories may not be the same for each vendor.

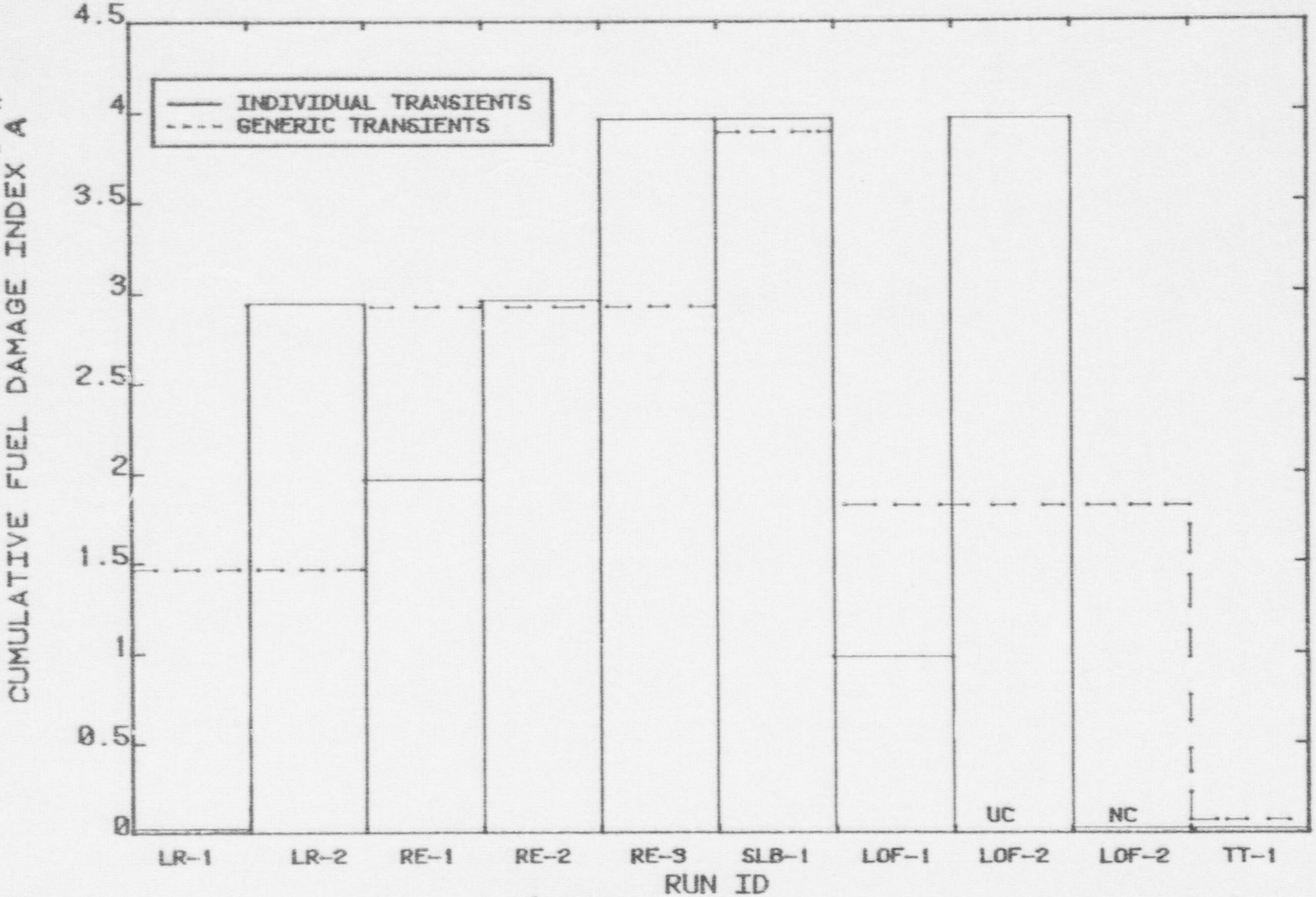

FIG. 8 METHOD (A):(THRESHOLD CRITERIA-GRAPHICAL PARAMETERS)

Cumulative fuel damage potential for different transients.

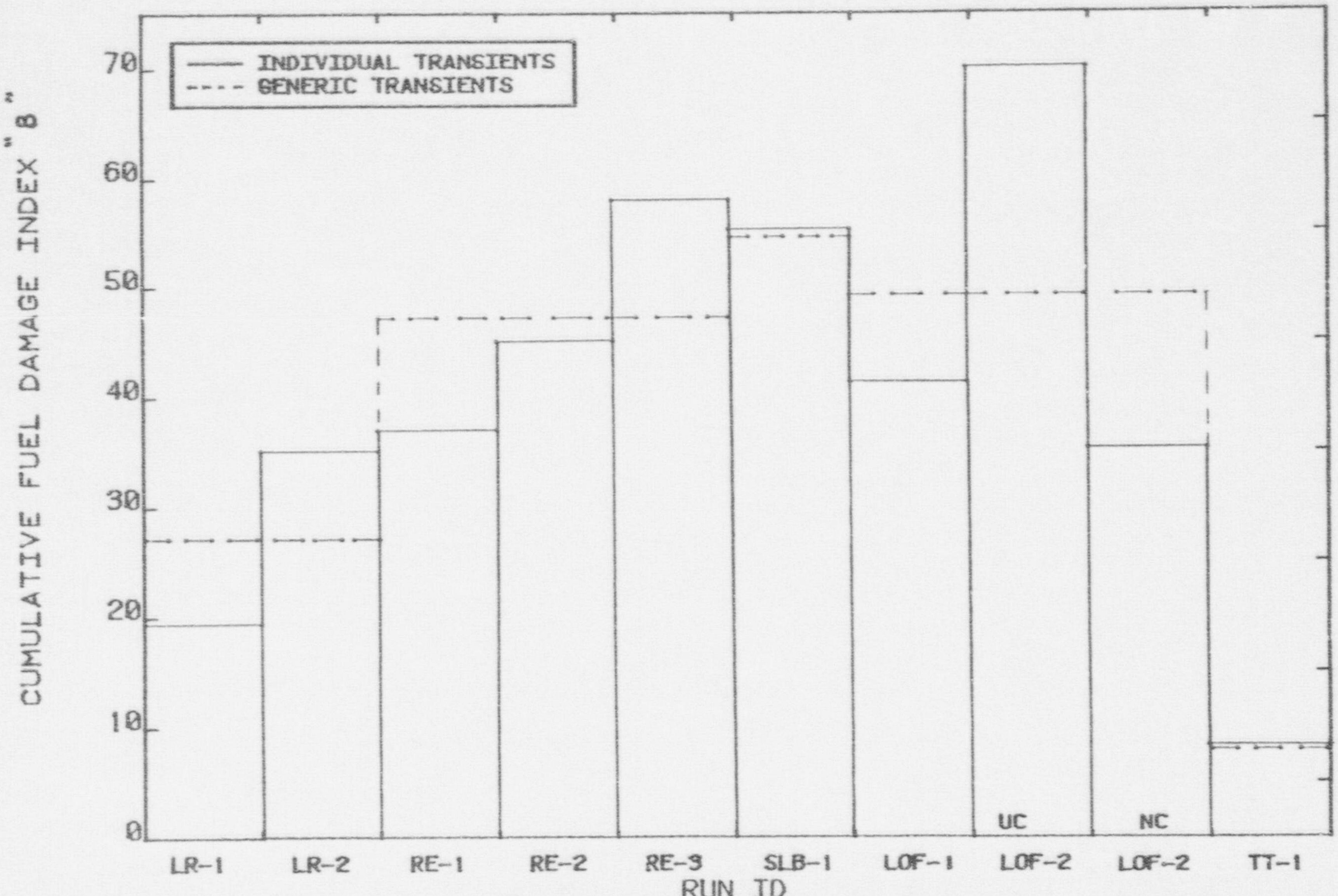

FIG. 9 METHOD (B):(RELATIVE DAMAGE RANKING-TABLE III PARAMETERS)

Cumulative fuel damage potential for different transients.

TABLE IV

CUMULATIVE FUEL DAMAGE POTENTIAL FOR INDIVIDUAL RUNS AND GENERIC TRANSIENTS

	Method (a): Threshold Criteria Index, 0 or 1		Method (b): Relative Damage Index, 1 thru 10	
	Damage Potential	Run ID	Damage Potential	Run ID
Highest	1	LOF2 (UC)	1	LOF2 (UC)
	1	RE3	2	RE3
	1	SLB1	3	SLB1
	2	RE2	4	RE2
	3	LR2	5	LOF1
	4	RE1	6	RE1
	5	LOF1	7	LR2
	6	LOF2 (NC)	7	LOF2 (NC)
	7	LR1	8	LR1
Lowest	8	TT1	9	TT1
	Damage Potential	Generic Transient	Damage Potential	Generic Transient
Highest	1	SLB	1	SLB
	2	RE	2	LOF
	3	LOF	3	RE
	4	LR	4	LR
Lowest	5	TT	5	TT

VII. RECOMMENDATIONS

Recommendations arrived at as a result of analyzing lead rod operating transients with FRAP-T4 address needs in three areas; namely model development and supporting analysis, uncertainty analysis of predictions, and data analysis.

Model Development and supporting analysis needs can be summarized as follows:

1. more realistic treatment of pellet relocation, crack healing, and gas release effects on thermal, mechanical, and pressure response.

2. Incorporation of a transient closed channel option for calculating fluid conditions.

3. Scoping studies of burnup (FRAPCON) and open channel (COBRA) effects on fuel damage predictions.

Error analyses are necessary to quantitatively account for the integral effects of model and input uncertainties on fuel damage predictions. The graphically expressed damage criteria shown in Figures 1 through 7 were often either met or exceeded on the basis of the model uncertainty range assumed. The distribution of model predictions over this range as well as the range itself should be checked. The fuel damage effects of relative channel power variation and system condition uncertainty should also be evaluated. In this way, the effects of different assumptions being reflected in the vendor-supplied power and system histories can be accounted for. The current prediction uncertainties only account for model error effects on the hot channel under nominal (given) power and cooling conditions.

Data analysis should be applied to determining best estimate fuel damage criteria. The constraints of physical property limitations

should be emphasized. Currently used criteria should be evaluated and more mechanistic alternatives developed in view of present fuel behavior understanding and integral experiment results.

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