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DOCUMENT TITLE

Fuel Element Vibration Study - Design and Analysis of a
Pre-Kinked Column Buckling Device

AUTHOR

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ABSTRACT

The column buckling device fuel element vibration suppressor has been analyzed and re-designed. Pre-kinking of the column shows resultant lowering of the strain hardening effects of a straight column and the axial deformation required to sustain the total column load.

Design of the new CBD is presented and further recommendations are included.

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I. INTRODUCTION

Development of a launch vibration suppression device has involved the investigation of several possible designs (Ref. 1). The most promising device, which best conformed to the design criteria (Ref. 1), was the column buckling device (CBD). Analysis and testing of a suitable CBD to be compatible with the current reference ZrH design has continued through the present (Ref. 2-9). However, recent investigation into fabrication processes has revealed the necessity of placing the CBD in the cup plug end (inlet) of the fuel element rather than the hotter, blind end (outlet). The collapse load during various phases of operation can effect stressing of the clad and hydrogen barrier. Thus, further analysis and experimental verification must be performed to stabilize the vibration suppressor design point. Design and Analysis of the CBD is reported in sections II - IV assuming that the column could collapse during at-power operation (long-term creep collapse) or during a transient (short-term collapse at scram). However, the collapse mode discussion is dependent upon the generated loads in the CBD and thus, this section (V) is presented after the loading analysis.

II. CURRENT CBD DESIGN - ANALYSIS & EXPERIMENT

Collapse loads for various design CBD's have been experimentally determined at different temperatures. The pertinent data from these tests appears in Table I. Load versus deflection curves for certain of these tests appear in Figures 1 - 10. The data from this table has been used to study various analytical approaches to the CBD design problem. Calculations using the standard Euler equation for long columns (Ref. 10, 11, 12) and the Reduced Euler Equation (for buckling beyond the proportional limit) (Ref. 12-16) have been compared with the experimental data. These methods predict total column load capability two orders of magnitude above the measured loads, and are therefore not applicable to the problem at hand. However, the secant equation (Ref. 7, 10, 11) predicts column loads which are only somewhat lower than the reported loads of Table I. A short discussion of the secant

PREPARED BY RVA	ATOMICS INTERNATIONAL A Division of North American Rockwell Corporation	PAGE 3
CHECKED BY		OF
DATE Jan 22, 1971	TABLE 1: CBD DATA	REPORT NO. TI-759-240-031
		MODEL NO.

Experimental Data for CBD development (Ref 24)

TEST NUMBER	DESIGN MATERIAL	END DESIGN TYPE	COLUMN LENGTH (IN)	Column Diameter (in)	Test Temp. (°F)	Reported Collapse Load, P (Lbs)	Stress for Collapse P/A (KSI)	* indicates P-δ curve available	
101	502SS	2 flt	0.45	45	70 (RT)	79.5	50.0	*	
102						76.0	47.8	*	
103						76.0	47.8	*	
104						69.0	43.4	*	
105				↓		69.0	43.4	*	
201				52		111.0	52.4	*	
202						116.0	54.6	*	
203						118.5	55.9	*	
204		↓		↓		118.5	55.9	*	
301		1 flt / round		49		93.0	49.1	*	
302						86.0	45.5	*	
303						90.0	47.6	*	
304				↓		90.5	47.8		
401				45		61.0	43.4	*	
402		↓		↓	↓	66.0	41.5	*	
501		2 flt		52	1100	59.5	28.1	*	
502						73.5	24.7		
503					↓	64.5	30.4		
601					1350	28.0	13.2	*	
602						28.5	13.4	*	
603	↓	↓		↓	↓	28.0	13.2	*	
701	405SS	round / flt		53	70 (RT)	92.0	41.6	*	
702						88.5	40.1	*	
703					↓	94.0	42.5	*	
801					1350	10.0	4.53	*	
802						10.5	4.75	*	
803				↓	↓	11.0	4.96	*	
901				52	70 (RT)	87.5	41.2	*	
902	↓	↓	↓	↓	↓	91.5	43.1	*	

FIGURE 1 CBD Collapse Curves

No. TI-759-240-031
Page 4

Part No. 1012

BALDWIN-LIMA-HAMILTON CORPORATION, WALTHAM, MASSACHUSETTS

Printed in U.S.A.

Test #: 101

102

103

Design: 502 ss wire; annealed 100 hrs @ 1400°F;
Furnace cooled in vacuum; 0.045" diameter;
2 flat ends (H); 0.45" long

Data: 2 samples at R.T. (70°F)

Collapse rate is 0.002 in/in/min

FIGURE 2

No. TI-759-240-031
Page 5

CBD Collapse Curves

Chart No. 1012

BALDWIN-LIMA-HAMILTON CORPORATION

Test: 104

105

Design: 502 ss wire; annealed 100 hr @ 1400°F;
furnace cooled in vacuum; 0.045" diameter;
2 flat ends (H); 0.45" long

Data: 2 samples at R.T. (70°F)

Collapse Rate is 0.002 in/in/min.

FIGURE 3

CBD Collapse Curves

No. TI-759-240-031
Page 6

DWIN-LIMA-HAMILTON CORPORATION, WALTHAM, MASSACHUSETTS

Printed in U.S.A.

Test #: 201 202 203 204

Design: 502 ss wire ; 0.052" dia; annealed 100 hr
@ 1400°F — furnace cooled in vacuum;
2 flat ends (H); 0.45" long

Data: P-δ curve - 4 samples at R.T. (70°F)

Collapse rate = 0.002 in/in/mm

FIGURE 4

No. TI-759-240-031
Page 7

CBD Collapse Curves

Design: 502 ss wire; 0.049" dia; annealed 100 hr
 @ 1400°F — furnace cooled in vacuum;
 reference ends — 1 round/1 flat (1→); 0.45" long

Data: P-E curve; 3 samples at R.T. (70°F)

Collapse rate = 0.002 in/in/mm

FIGURE 5

CBD Collapse Curves

No. TI-759-240-031
Page 8

Test #: 402

401

Design: 502 ss wire; annealed 100 hr. @ 1400°F;
Furnace cooled in vacuum; 0.045" diameter;
reference ends - 1 flat/1 round (1); 0.45" long

Data: 2 samples at R.T. (70°F)

Collapse rate = 0.002 in/in/min

FIGURE 6

No. TI-759-240-031
Page 9

CBD Collapse Curve

Test #: 501

Design: 502 ss wire; 0.052" dia; annealed 100hr
@ 1400°F - furnace cooled in vacuum;
2 flat ends; 0.45" long

Data: P-6 curve; 1 sample at ~1100°F

Collapse rate = 0.002 in/in/min

FIGURE 7

CBD Collapse Curves

Design: ~~502~~ 502 ss wire; 0.052" dia.; annealed 100 hr.
@ 1400°F - furnace cooled in vacuum;
2 flat ends; 0.45" long

Data: P-E curve - 3 samples at ~ 1350°F

Collapse rate = 0.002 in/in/min

FIGURE 8 CBD Collapse Curves

Reported Collapse Load

Chart No. 1012

BALDWIN-LIMA-HAMILTON CORPORATION, WALTHAM, MASSACHU

Test #:

701

702

703

Design: 405 ss wire; annealed 100 hrs @ 1400°F; furnace cooled in vacuum; 0.053" diameter; reference design - 1 flat/wound end (←); 0.45" long

Data: 2 samples at R.T. (70°F)

Collapse Rate is 0.002 in/in/min

CBD Collapse Curves

Design: 405 ss; annealed 100 hrs @ 1400°F.; furnace cooled in vacuum;
0.053" dia; reference design - 1 flat/1 round end (F-1); 0.45" long
Data: 3 samples at 1350°F.
Collapse Rate is 0.002 in/in/min.

FIGURE F0 CBD Collapse Curves

No. TI-759-240-031
Page 13

BALDWIN-LIMA-HAMILTON CORPORATION, WALTHAM, MASSACHUSETTS

Printed in U.S.A.

Test #: 901

902

Design: 405 ss wire; annealed 100 hr @ 1400°F -
furnace cooled in vacuum; 0.052" dia; reference
ends - 1 flat/1 round (→); 0.45" long

Data: 2 samples at R.T. (70°F)

Collapse rate = 0.002 in/in/min

equation follows. The formulation is based on a statistical analysis of real column behavior (since no column is perfectly straight or the applied loads perfectly concentric). Thus, for the design of a real column, a probable crookedness translated into an effective load eccentricity may be assigned. We therefore have

$$\sigma_{\max} = \frac{P}{A} \left[1 + \left(\frac{ec}{r^2} \right) \secant \frac{L}{r} \sqrt{\frac{P}{4EA}} \right] \quad (1)$$

where

- $\sigma_{\max}$ = maximum fiber stress at yield - yield point (for alloyed steels) (Ref. 11)
- P = column load at failure
- A = column cross-sectional area
- e = equivalent eccentricity
- c = distance from central bending axis to extreme fiber on compression side of member = column radius for "straight" column = R
- r = radius of gyration for column = $1/2R$ for circular column
- $\left(\frac{ec}{r^2} \right)$ = Ecc = eccentric ratio for column ≈ 0.25 for "straight", short column (Ref. 11)
- L = effective column length = distance between points of inflection
- E = elastic modulus

Referring to Figure 11, we note that the effective length of the CBD column is approximately $L_{\text{total}}/2$. Figure 12 illustrates the effects of column offset on the failure mode. It should be noted that the misnomer eccentricity has been used to label the offset effect. Due to the fixed end design of the CBD, and the parallel alignment of the CBD end caps (resulting from

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CHECKED BY:		REPORT NO. TI-759-240-01
DATE: 7/24/71	FIGURES 11.1 and 12	MODEL NO.

FIGURE 11 - Effective Length of CBD

FIGURE 12 - Offset Column Effects

the parallel loading of the fuel), any statistical analysis of the column can only establish that concentric loading exists with any amount of offset. Thus, offset has no effect on collapse load.

Data correlation is presented in Table II. The values in column 4 have been calculated using Equation (1) with $\sigma_{\max} = 0.2\%$ offset yield strength at given temperature, and $Ecc = 0.25$. Note that these values are only 70-85% of the reported failure loads in column 7. The secant collapse loads have been plotted on Figures 1-10, and a review of the curves reveals that the secant equation is predicting the load at the initiation of plastic deformation. This is especially demonstrated in Figures 1-4. Thus, the elastic behavior of the CBD is entirely predictable analytically. This loading will be further denoted as the maximum elastic loading.

The maximum elastic load is the design load for the CBD during launch vibration. This becomes obvious by noting that any plastic (non-recoverable) axial deformation of the column results in increased loading (due to greater axial fuel freedom of motion) of the CBD. Increased loading promotes further deformation, thus the column must be designed to a given safety factor within the elastic design. The design point of the CBD is therefore analytically predictable.

The reported loads are such that further collapse requires diminished loading and will be denoted as the maximum plastic collapse loads. That these loads exist above the maximum elastic loading is a strain-hardening phenomenon. The plastic strain-hardening effect is demonstrated in Fig. 13. Note that the compressive stress which exists above the proportional limit of the material exists only on the concave side of the column, and exists only during a state of initial buckling. Thus, the additional loading from the maximum elastic load to the maximum plastic collapse load is a function of the rate of strain hardening (and thus the rate of loading or deformation) and the stability of the state of initial buckling.

PREPARED BY RVA	ATOMICS INTERNATIONAL A Division of North American Rockwell Corporation	PAGE 17 OF
CHECKED BY		REPORT NO. TI-759-210-031
DATE Jan 22, 1971	TABLE 2 : SECANT CALCULATIONS	MODEL NO.

SECANT CALCULATIONS IN $\oplus$ use $G_{max} = .2\%$ offset yield stress (col. ③)
 column ③ data from USS steel and Carpenter Steel handbooks -
 (extrapolated to 1350°F).

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
TEST NUMBER	MATL/ TEMP (°F)	.2% off yield stress (annealed) (KSI)	MAX LOAD FROM SEC. EQN. WITH ECC=.25 (LBS.)	OFFSET LOAD FROM COLLAPSE CURVES (LBS)	⑤-④ (LBS)	COLLAPSE LOAD, P (from Table 1) (LBS)	⑦-④ ΔP_{calc} (LBS)	⑦-⑤ $\Delta P_{exp.}$ (LBS)	% collapse $\frac{④}{⑦} \times 100\%$
101	502/70	50.0	62.8	62.5	-0.3	79.5	16.7	17.0	79.0
102				61.0	-1.8	76.0	13.2	15.0	82.6
103				60.0	-2.8	76.0	13.2	16.0	82.6
104				—	—	69.0	6.2	—	91.0
105			↓	58.5	-4.3	69.0	6.2	10.5	91.0
201			84.2	85.0	0.8	111.0	26.8	26.0	75.8
202				83.0	-1.2	116.0	31.8	33.0	72.5
203				82.5	-1.7	118.5	34.3	36.0	71.0
204			↓	84.3	0.1	118.5	34.3	34.2	71.0
301			74.6	—	—	93.0	18.4	—	80.4
302				75.0	0.4	86.0	11.4	11.0	86.9
303				—	—	90.0	15.4	—	83.0
304			↓	NO CURVE	—	90.5	15.9	—	82.5
401			62.8	—	—	69.0	6.2	—	91.0
402	↓	↓	↓	—	—	66.0	3.2	—	95.2
501	502/1100	15.0	25.4	—	—	59.5	34.1	—	42.6
502				NO CURVE	—	73.5	48.1	—	34.6
503	↓	↓	↓	NO CURVE	—	64.5	39.1	—	39.4
601	502/1350	~9.0	15.3	24.7	9.4	28.0	12.7	3.3	54.6
602				—	—	28.5	13.2	—	53.6
603	↓	↓	↓	—	—	28.0	12.7	—	54.6
701	405/70	41.0	71.8	~73.5	1.7	92.0	20.2	18.5	78.0
702				—	—	88.5	16.7	—	81.2
703	↓	↓	↓	—	—	94.0	22.2	—	76.4
801	405/1350	5.4	9.5	5.0	-4.5	10.0	0.5	5.0	95.0
802				5.3	-4.2	10.5	1.0	5.2	90.5
803	↓	↓	↓	5.1	-4.4	11.0	1.5	5.9	86.4
901	405/70	41.0	69.1	—	—	87.5	18.4	—	79.0
902	↓	↓	↓	—	—	91.5	22.4	—	75.5

PREPARED BY: RVA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 18 OF
CHECKED BY:		REPORT NO. TI-759-240-031
DATE: 7/24/71	FIGURE 13	MODEL NO.

Strain Hardening of CBD due to Initial Buckling

This section of column is strain-hardening due to plastic deformation. This offers a resistance to further Buckling.

Again, referring to the load-deflection curves, the axial CBD deformation during the strain hardening phenomenon can be obtained. Measurement of these deformations are illustrated in Figure 14. The data is presented in Table III. The method of predicting the bowing due to axial deformation (as listed in Table III) is shown in Figure 15. Note that this method overpredicts the bowing but qualitatively demonstrates the effects of kinking versus strain-hardening.

The last column in Table III demonstrates the correlation between column diameter and bowing to realize the maximum plastic collapse load. When this condition exists, it can be seen that the position of the central bending axis (see Figure 13) is such that the buckling moment generated by the load at the offset center of the column exceeds the opposite moment generated by the strain hardening phenomenon. This is in direct proportion to the column diameter. The larger the column diameter, the greater axial deformation is required to reach the maximum plastic collapse load.

Note also that the difference between the maximum plastic collapse load and the maximum elastic load (see Table II: columns 8 and 9) also correlates (within large limits) to column diameter. Thus, diameter determines the duration of the deformation required for maximum plastic collapse and also the magnitude of the plastic strain-hardening for a "straight" column. However, were it possible to decrease the axial deformation necessary to cause full plastic collapse, and also the maximum plastic collapse load, the total maximum load generated by the CBD in the element would decrease. In addition, the possibility of realizing this load during a transient (shutdown) would diminish.

Pre-kinking of the CBD can provide the needed load and deformation decrease. A discussion of analytical methods for pre-kinked column load capability prediction follows.

PREPARED BY: RVA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 20 OF
CHECKED BY:		REPORT NO. TI-759-240-031
DATE: 4/26/71	FIGURE 14	MODIFY NO.

Sample Collapse Curve (Load-Deflection)
for "straight" CBD

NO SCALE

TABLE III

STRAIN HARDENING: AXIAL DEFORMATION AND
COLUMN BOWING EFFECTS

Test No. *	ΔL_1 ** (mils)	ΔL_2 (mils)	B, *** bowing resulting from ΔL_2	B/Col Dia x100%
101	6.0	13.0	27.0	60.0
102	5.4	12.0	25.0	55.5
103	6.0	13.0	27.0	60.0
105	12.0	12.0	25.0	55.5
201	6.0	15.0	29.0	55.8
202	5.0	17.0	31.0	59.5
203	6.0	17.0	31.0	59.5
204	7.0	17.0	31.0	59.5
302	8.0	12.0	25.0	51.0

* Only measurable tests have been included.

** The assumption has been used that all bowing results from ΔL_2 only.

*** B is assumed to be 1/2 of the bowing predicted by the model in Figure 15.

PREPARED BY: RVA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 22 OF
CHECKED BY:		REPORT NO. TT-759-210-031
DATE: 1/26/71	FIGURE 15	MODEL NO.

Prediction Method For Bowing

$$\left(\frac{L}{4}\right)^2 = \left(\frac{L}{4} - \frac{\Delta L_2}{2}\right)^2 + B^2$$

$$B^2 = \frac{L \Delta L_2}{4} - \frac{\Delta L_2^2}{2} \quad \text{negligible}$$

$$B \approx \frac{\sqrt{L \Delta L_2}}{2}$$

$$\text{for } L = .45$$

$$B \approx \frac{\sqrt{\Delta L_2}}{3}$$

III. PRE-KINKED CBD DESIGN - ANALYSIS

The applicability of the secant formulation to the present design led to investigation of a similarly derived equation for pre-bent short columns (Ref. 11).

$$\sigma_{\max} = \frac{P}{A} \left\{ 1 + \frac{B_c}{r^2} \frac{8EA}{P(L/r)^2} \left[\sec \left(\frac{P}{4EA} \left(\frac{L}{r} \right)^2 \right)^{1/2} - 1 \right] \right\} \quad (2)$$

The nomenclature is similar to that for Equation (1) and in addition:

L = effective column length = distance between points of inflection
= $L_{\text{total}}/2$

B = effective maximum initial deflection = 1/2 of maximum distance from centerline of unbent section to centerline of bent section (a result of the effect of fixed ends versus pinned ends)

For comparison, a plot of calculated collapse load (maximum elastic load) for a "straight" and pre-kinked column is presented in Figure 16. Note that the "straight" column is designed for maximum elastic collapse (with $Ecc = 0.25$) and the maximum plastic load is assigned by adding an estimated strain-hardening load differential. In comparison, the pre-kinked column has a smaller plastic deformation effect because it is designed with an initial deflection. Thus, for pre-kinking, the elastic and plastic loadings are very close. The design diameter of the kinked column therefore must be greater in that (1) the design load is to be taken as the elastic load, and (2) the large initial deflection reduces the loading capabilities of the column.

IV. EXAMPLE DESIGN OF "STRAIGHT" AND PRE-KINKED CBD's

At the present time, no analysis has been performed to establish the total effective static load exerted by the segmented fuel during launch vibration. Thus, design of the CBD can only proceed to establish load/column diameter relationships. However, it is interesting and informative to assume a design load and establish design parameters for the two CBD's.

We assume a total effective static load at 70°F of 90 pounds. The CBD design material is chosen as 405 SS for its yield strength versus temperature properties and its tendency not to air-harden (aluminum additive).

$\sigma_{\max} = 41000$ psi at 70°F (Ref. 19). The elastic modulus is 30,000,000 psi (Ref. 24). The remaining design parameters appear in Table IV below:

TABLE IV

"STRAIGHT" COLUMN

Max. plastic collapse load	= 90.	pounds at 70°F
Max. elastic load (0.8 x plastic)	= 72.	pounds at 70°F (Design Load)
Column length	= 0.45	inches
Effective eccentricity (nominal)	= 0.25	
Column diameter	= 0.053	inches
Axial deformation required to sustain max. plastic load	= 0.015	inches at 70°F

PRE-KINKED COLUMN

Max. plastic collapse load	= 76.	pounds at 70°F
Max. elastic load (.95 x plastic)	= 72.	pounds at 70°F (Design Load)
Column length	= 0.45	inch

<u>Initial Deflection (mils)</u>	<u>Column Diameter (inch)</u>	<u>Axial deformation to sustain $P_{\max}$ (inches)</u>
10	0.061	0.013
12	0.063	0.012
15	0.066	0.010

V. CBD COLLAPSE MODES

There are two possible collapse modes for the CBD:

1. Long-term collapse mode:

The normal, at-power mode of collapse for the CBD is initiated by axial fuel swelling. A plot of axial fuel growth versus time for a ring one element in the core test reactor is reported separately (as a classified document) in Ref. 17. It can be inferred from this plot and the fuel swelling correlation that the maximum creep rate applied to the CBD column is 0.01%/hr (a conservative estimate which decreases rapidly with time). From Fig. 17 (Ref. 19) the maximum stress generated in the column due to this creep rate is estimated to be 16,000 psi (assuming CBD operated at approximately 1100°F). Assuming a maximum column diameter of 0.070", the stress corresponds to a cladding load of 62 pounds, or a cladding stress of approximately 1000 psi. Fig. 18 (Ref. 18) demonstrates that this stress generates a negligible creep rate in the Incalloy 800 cladding. Thus, the long term mode of collapse would seem to have no adverse effects on the fuel element.

2. Short-term collapse mode:

There exists the possibility of a short-term collapse in which the entire column load is generated in the cladding. The collapse load of the CBD is dependent upon the operating temperature and the point in lifetime at which the short-term deformation occurs. Fig. 19 illustrates a short-term collapse during an early lifetime scram to room temperature (Refs. 22 and 23). Fig. 20 shows the effect of a shutdown axial fuel CBD gap for a ring one element undergoing a change from an operational temperature profile to a given isothermal core temperature.

Returning to the nomenclature of Fig. 14, we define $\Delta L_{\text{collapse}} = \Delta L_1 + \Delta L_2$ to be the total axial deformation required to attain the maximum plastic collapse load. Minimizing $\Delta L_{\text{collapse}}$ is preferable. The effects of

100,000

FIGURE 18 SECONDARY CREEP RATE - UNIAXIAL -

- INCOLOY 800 -

$$\dot{\epsilon}_2 = 4.3369 \times 10^{-11} \sigma^{7.51322} e^{-93783.5/T \cdot R}$$

PREPARED BY: R9A	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 29 OF
CHECKED BY:		REPORT NO. TI-759-240-031
DATE: 1/14/71	FIGURE 19	MODEL NO.

Short Term Collar Button Collapse Mode

#1

Room Temp.

B.O.L., $t = 0$

5 mil Axial Gap (Assembly Tolerance)

#2

Operating Temp

B.O.L., $t = 0$

~50 mil Axial Gap

#3

Operating Temp.

$t = t_0$

0 mil Axial Gap

~50 mil Axial Swelling

#4

Room Temp, isothermal

$t = t_0$

After Scram,

~45 mil Collapse

NO SCALE

the large $\Delta L_{\text{collapse}}$ which exists with the "straight" column design is well demonstrated in Fig. 21, in which the "straight" column of Table IV has been analyzed using the CBALLS (Column Behavior At Low Level Swelling) code on the Honeywell ± 30 system. A listing of CBALLS appears in Appendix A. CBALLS correlates the effects of (1) Secant calculations of the maximum elastic load using temperature dependent yield strength data for 405 stainless steel (Fig. 22), (2) strain hardening on the maximum plastic collapse load using an experimentally determined temperature correlation, (3) differential expansion between the fuel and cladding as shown in Fig. 20, (4) variation of $\Delta L_{\text{collapse}}$ with temperature as determined from the experimental data, (5) variation of the generated column load with axial deformation of the CBD as determined from the experimental data, and (6) decrease in the generated column load with increased axial deformation after reaching the maximum plastic collapse load (as extrapolated from the experimental data).

Assuming that the reactor has been shut down from an operating temperature profile to an isothermal inlet temperature condition, followed by further reduction in isothermal core temperature to T_0 , the total column load generated at T_0 can be found from Fig. 21 as a function of axial fuel swelling (assuming a 0.005" axial assembly gap at room temperature). This can then be correlated to a reactor operating lifetime through Ref. 17. Note that the analytical methods in CBALLS are valid only for axial fuel swelling less than that amount, ΔL_{crit} , necessary for fuel CBD contact during operation. No CBD creep evaluation curves are in existence at the present time and the effects of high temperature buckling through creep cannot be evaluated. Thus, no curves exist in Fig. 21 for $\Delta L_{\text{fuel swell}} > \text{Axial assembly gap} + 0.044''$ (where 0.044" is the differential expansion gap in going from an isothermal room temperature core to an operating temperature profile).

P, Load Generated in Column, lbs.

FIGURE 2.1

Total Load Generated in CBD

UNDER FOLLOWING CONDITIONS:

- 1) Core at operating temp. profile.
- 2) Core shutdown for inlet temp. (isothermal)
- 3) Core temp. (isothermal) reduced to T_0
- 4) 5 mil axial assembly gap
- 5) Incolloy 800 cladding

T_0 , Isothermal Core Temp, °F

VI. DISPLACEMENT OF THE COLLAPSED COLUMN

The CBD must be capable of sustaining an 0.250 inch axial deformation. The possibility of the outer column fiber contacting the ceramic hydrogen barrier upon column failure has been raised. Fig. 23 illustrates a "Worst-Case" collapse mode in which (1) the entire deformation is taken in a short section at the center of the column, (2) there is no length change in fibers on the compression side of the member, and (3) the deformed column section is perpendicular to the load centerline. Application to the pre-kinked column of Fig. 26 reveals that 0.25 inch collapse is possible and displacement is within the radius of the cup plug (with a maximum 0.060 inch cup plug wall). However, a length increase of the CBD column could be very beneficial in that (1) the total lateral displacement of a collapsed longer column will be less than that for a shorter column, (2) the length increase will cause only a second-order change in the design load, and (3) a 0.010 inch length increase allows design of an upper CBD loading plate which does not enter into the recessed cup plug (Fig. 24). Thus, the CBD design which follows is based upon an 0.55 inch column.

VII. CBD DESIGN: "STRAIGHT" VERSUS PRE-KINKED

Pre-kinking of the CBD results in a reduction of the strain-hardening effects: (1) the additional loading due to hardening is decreased, (2) the axial column deformation required to sustain the total load is decreased (Fig. 25). I, therefore, submit the preferred CBD design as outlined in Fig. 26.

VIII. CBD ELASTIC EFFECTS

The effective spring constant (K) for a "straight" column can be equated directly to the elastic modulus of the column material. This is well demonstrated in the initial (elastic) slope of the load-deflection curves (Fig. 1-10). This slope can be equated directly to the material modulus of elasticity (E). The correlation is strikingly close. Thus,

$$K = \frac{EA}{L} = \frac{E\pi R^2}{L}$$

PREPARED BY: RVA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 35 OF
CHECKED BY:		REPORT NO. TT-759-210-031
DATE: 1/26/71	FIGURE 23	MODEL NO.

Displacement of Collapsed Column

#1 BEFORE COLLAPSE

0.25 collapse possible if $\left(\frac{3L}{4} - d\right) > .25$

Collapse Assumptions:

1. No Column Length Change on Compression Side of Member (Worst Case Bend)
2. 0.25 Inch Collapse Minimum

#2 AFTER 0.25 INCH COLLAPSE

X = radius of bent column section

$$X = .125 + (1.5)d$$

AND $2X < D$ for no damage to cup plug

PREPARED BY: RYA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 36 OF
CHECKED BY:	FIGURE 24	REPORT NO. TI-759-210-031
DATE: 2/1/71		MODEL NO.

Schematic of Lengthened CBD Collapse

All dimensions in inches

NO SCALE

PREPARED BY, R/A	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 37 OF
CHECKED BY,		REPORT NO. TI-759-210-031
DATE, 2/1/71	FIGURE 25	MODEL NO.

Load - Deflection Curves for Pre-kinked VERSUS "Straight" CBD

Assume:

- 1) Pre kinked column diameter increased to sustain same design load as "straight" column
- 2) ~ 15 mils of prekinking

NO SCALE

PREPARED BY: RVA	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION	PAGE NO. 38 OF
CHECKED BY:		REPORT NO. TI-759-240-03
DATE: 2/1/71	FIGURE 26	MODEL NO.

Prekinked CBD Design

DESIGN MATERIAL: 405 SS FOR COLUMN

FABRICATION: PREKINK MAY BE DONE AT ANY POINT IN ASSEMBLY, BUT CBD MUST BE FULLY ANNEALED AFTER ASSEMBLY.

NOTE "A"- SLOPE INFLECTION POINT OF BEND SHOULD OCCUR AS CLOSE AS POSSIBLE TO ONE-FORTH OF THE TOTAL COLUMN LENGTH FROM THE END PLATES. THIS MOST CLOSELY APPROXIMATES THE NATURAL BENDING MODE.

SCALE: 5"=1"

For 405 stainless steel, we assume that $E = 30,000,000$ psi, $R = 0.0265$ inch, and $L = 0.45$ inch. Then $K = 14,700$ lbs/in. This corresponds to a natural resonance frequency (assuming direct attachment to a one pound mass fuel element) of 1200 hertz.

Unfortunately, a similar analysis is not applicable to a pre-kinked column in that lateral response to axial deformation could lower the effective spring constant. This has been illustrated qualitatively in Fig. 25. Furthermore, any analysis of elastic effects in a pre-kinked column would tend to be overly complex (i.e., finite element analysis). Experimental determination of the spring constant would, however, be inexpensive, simple, and accurate (in that the elastic modulus was accurately determined in the "Straight" column testing).

IX. SUMMARY OF RECOMMENDATIONS

Most of the following changes have been recommended or inferred in the previous sections, as noted. The remaining recommendations are substantiated below:

1. Pre-kinking of the column buckling device to minimize strain hardening effects during the short-term collapse mode. (Sec. II, III, IV, V, and VII).
2. Experimental testing of the pre-kinked CBD to determine the effective spring constant for the device. (Sec. VIII).
3. A 0.10 inch increase in the column length (from 0.45 to 0.55 inch) to eliminate upper CBD plate interference with the cup plug (and thus eliminate the necessity for the smaller diameter section of the fuel rod).
4. Reactor transient analysis to determine the possibility of other modes of collapse for the CBD. (To supplement the material of Section V).
5. Elimination of the ceramic coating on the upper plate of the CBD.

In that the primary function of the coating was removal of the possibility of fuel-metal interaction during high temperature operation (1350°F) and in that the CBD will now operate at lower temperatures (1100°F), I recommend that the coating be eliminated.

6. Investigation of local stressing of the ceramic barrier during short-term loading of the CBD at low temperatures.

The effects of a line contact in the cup plug could set up large stresses in the ceramic barrier. Increased hydrogen permeation rates could result from such stressing.

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APPENDIX A

No. TI-759-240-031
Page 42

CBALLS

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1C  CBALLS::: COLUMN BEHAVIOR AT LOW LEVEL SWELLING
2C
3C  THIS CODE USES SECANT FORMULATION AND
4C  EXPERIMENTALLY DETERMINED PARAMETERS TO
5C  CALCULATE THE CBD LOAD GENERATED BY SHUTTING
6C  DOWN THE REACTOR FROM AN OPERATING TEMPERATURE
7C  PROFILE TO AN ISOTHERMAL CORE TEMPERATURE,
8C  AS A FUNCTION OF AXIAL FUEL GROWTH.
1000SNM
110 REALT(21),SW(26),YS(21),FRACP(21),PMAX,P,L,LMAX
120 COMMONR,EFFL,ICNTL
130 DATAT/80,100,150,200,250,300,350,400,450,500,
140&550,600,650,700,750,800,850,900,950,1000,1035/
150 DATASW/0,0.005,.01,.015,.02,.025,.03,.035,.04,.045,.05,
160&.055,.06,.065,.07,.075,.08,.085,.09,.095,.1,
170&.105,.11,.115,.12,.125/
180C  YS ARRAY IS YIELD STRENGTHS OF 405 SS
190 DATAYS/41000,40500,39900,39100,38500,38000,
200&37400,36800,36400,36000,35500,35000,34200,33500,
210&32600,31600,30900,29500,28300,26400,19500/
220C  FRAC ARRAY DESCRIBES THE LOADING CURVE
230C  FOR THE CBD IN FRACTIONAL INCREMENTS
240C  OF PMAX AS A FUNCTION OF FRACTIONAL
250C  INCREMENTS OF LMAX.
260 DATAFRACP/0,.545,.68,.782,.815,.87,.92,.945,.977,
270&.99,.991,.992,.993,.995,.997,.999,1,.995,.99,.985,.98/
280 1000FORMAT(//
290&"      INIT ASSEMBLY GAP = ",3PF8.1," MILS"//
300&"      FUEL SWELLING      = ",3PF8.1," MILS"//)
310 1001FORMAT(OPF9.0,5X,OPF9.2)
320 1002FORMAT(
330&"      *FUEL-CBD CONTACT AT ",OPF7.0," DEGREES"//
340&"      TEMP              LOAD"//)
350 6969FORMAT(////)
360C  READ THE COLUMN DIAMETER, LENGTH, AND
370C  THE INITIAL (ROOM TEMP) AXIAL GAP
380 1PRINT," DIA, L, ASSEMBLY GAP",+*
390 READ(50,),DIA,L,GAPI
400 R=DIA/2
410 EFFL=L/2
420C  DO-LOOP FOR VARIOUS SWELLINGS
430 DO500ISW=1,26
440C  CALCULATE GAPX: THE OPERATIONAL GAP FOR
450C  A GIVEN FUEL SWELLING
460 GAPX=GAPI+0.0438461-SW(ISW)
470C  CALCULATE TCEN: THE CONTACT TEMPERATURE
480C  FOR THIS SWELLING
490 TCEN=650-13000*GAPX
500 PRINT 1000,GAPI,SW(ISW)
510C  CHECK GAPX FOR OPERATIONAL CONTACT

```

CBALLS CONTINUED

```
520 IF(GAPX.LT.0)GOTO69
530 PRINT 1002,TC0N
540C D0-L00P FOR TEMPERATURE ARRAY
550 D0400IT=1,21
560 DELLSW=(T(IT)-650)/13000
570C CALCULATE GAP: THE GAP AT A GIVEN TEMP
580 GAP=SW(ISW)-GAPI-0.0438461-DELLSW
590 IF(GAP.LE.0)GOTO499
600 SMAX=YS(IT)
610 XI=SMAX*3.14*R*R
620C USE NEWTON-RAPHSON ITERATION TO CALCULATE
630C PMAX FROM SECANT EQUATION
640 CALLNEWT(SMAX,XI,0.01,0.5,0.002,500,NF,YF,XF)
650C CALCULATE PMAX INCLUDING STRAIN HARDENING
660 PMAX=XF*(YS(IT)**0.0643)/1.55
670C CALCULATE LMAX: THE DELTA LENGTH OF CBD AT
680C WHICH PMAX REDUCES BACK TO .98*PMAX
690 LMAX=0.03-(PMAX-10)/8200
700C IF GAP EXCEEDS LMAX, USE DIFFERENT CALCULATION FOR LOAD
710 IF(GAP.GT.LMAX)GOTO299
720C USE FRAC ARRAY TO CALCULATE POSITION OF COLLAPSE CURVE
730 FRACI=GAP/LMAX
740 IGAP1=IFIX(FRACI/0.05)+1
750 IGAP2=IGAP1+1
760 FRACI1=FRACI-(IGAP1-1)*0.05
770 FRACP1=FRACP(IGAP2)-FRACP(IGAP1)
780 FRACPA=FRACP(IGAP1)+FRACP1*FRACI1/0.05
790 P=PMAX*FRACPA
800 GOTO300
810 299CONTINUE
820 GAPR=GAP-LMAX
830C CALCULATE LOAD IS DELTA LENGTH GREATER THAN LMAX
840 P=0.98*PMAX-25*GAPR/0.016
850 IF(P.LE.0)GOTO499
860 GOTO300
870 499P=0
880 GOTO300
890 300PRINT 1001,T(IT),P
900 400CONTINUE
910 500CONTINUE
920 PRINT 6969
930 GOTO1
940 69PRINT," FUEL HAS CONTACTED CBD"
950 PRINT 6969
960 GOTO1
970 END
1000 SUBROUTINENEWT(YS,XI,DX,DXM,EPS,N,NF,YF,XF)
1010C NEWTON-RAPHSON ITERATION METHOD
1020 REALP,L,PI,ECC
1030 1X2=XI
```


CBALLS CONTINUED

```
1040 DEL=DX*X2
1050 D0300I=1,N
1060 Y2=FNEW(X2)
1070 IF(I.EQ.1)G0T020
1080 100IF(ABS((Y2-YS)/YS).LE.EPS)G0T0200
1090 DEL=-(Y2-YS)/(Y2-Y1)*(X2-X1)
1100 DEL=SIGN(AMIN1(ABS(DEL),ABS(DXM*X2)),DEL)
1110 20X1=X2
1120 X2=X2+DEL
1130 300Y1=Y2
1140 900PRINT 902
1150 902FORMAT(// " WARNING---MAXIMUM NUMBER OF ITERATIONS"//)
1160 I=N
1170 200XF=X2
1180 YF=Y2
1190 NF=I
1200 RETURN
1210 END
2000 FUNCTIONFNEW(X)
2010C SECANT EQUATION FOR NEWTON-RAPHSON
2020 COMMONR,EFFL,ICNTL
2030 F=SQRT(X/9.42E7)
2040 F=EFFL*F/(R*R)
2050 F=1+0.25/COS(F)
2060 F=X*F/(3.14159*R*R)
2070 FNEW=F
2080 RETURN
2090 END
```