MECHANICAL SUPPORT DEPARTMENT
ENGINEERING NOTE

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DATE: January 1995

TITLE: Vacuum Window Failure Analysis

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KEY WORDS: KTeV Vacuum Window Failure, Vacuum System, Vacuum, Decay Region, Decay

ABSTRACT/SUMMARY:

This design note contains the calculations and analysis necessary to understand the effect on the vacuum vessels, the building, and on SA2 in the event that the vacuum window fails suddenly while the vacuum window safety barrier is in the open (or up) position.

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SUBJECT: VACUUM VOLUMN:

NAME: DANE PUSHKA

DATE: 5 DEC '94

REVISION DATE:

VESSEL	I.D	LENGTH	Wt
TRANSITION	94.5 ø	11"	2962#
RC 10	94.5" ø	8.25"	12,000 #
VV 9/10	94.5" ø	228"	18,700 #
RC 9	94.5" ø	8.25"	12,000 #
VV 8/9	94.5" ø	228"	18,700 #
RC 8	94.5" ø	8.25"	12,000 #
VV 7/8	78.75" ø	306"	16,846 #
RC 7	78.75" ø	8.25"	9200 #
VV 6/7	78.75" ø	228"	13,300 #
RC 6	78.75" ø	8.25"	9200 #
VV R/6	78.75" ø	266"	14,274 #
REGENERATOR	71.25" ø	216.5"	16,600 #
201860	48" ø	10'-5 (125")	3500 #
20194	48" ø	14'-3 (171")	4300 #
201862	48" ø	14'-10¼ (178.75")	4400 #
201863	48" ø	10'-4 (124")	3000 #
285024	29" ø	40.75"	700 #
284137	29" ø	84.09"	1200 #
284136	29" ø	66.56"	950 #
284135	29" ø	75.53"	1060 #
BEAM PIPE	13.25" ø	≈ 360" (30'-0) @ 55 #/FT	= 1650 #
110-4-72	≈ 10"x 4"	≈ 72" @ 10 #/FT	= 60 #
DC	≈ 12" ø	≈ 120" (10'-0)	N/A (BELLOWS)
BURRIED B.P	12" ø	≈ 780" (65'-0)	N/A "
NM2 B.P.	≈ 8" ø	≈ 1560" (130'-0)	N/A "
MU SCORED II	≈ 4" ø	≈ 240" (20'-0)	N/A "
TOTAL VOLUMN.		5526 FT³	176602#

VOLUMN OF WINDOW TEST TABLE 30.7 FT³
WIEGHT OF " " " 4250 #

≈ ESTIMATED.

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vacuum volumn - 2

Item	I.D. (in)	Length (in)	Volumn (in3)	Weight (#)
Transition	94.5	11	77151.82	2962
RC10	94.5	8.25	57863.87	12000
VV 9/10	94.5	228	1599146.84	18700
RC9	94.5	8.25	57863.87	12000
VV8/9	94.5	228	1599146.84	18700
RC8	94.5	8.25	57863.87	12000
VV7/8	94.5	306	1490432.91	16846
RC7	78.75	8.25	40183.24	9200
VV6/7	78.75	228	1110518.64	13300
RC6	78.75	8.25	40183.24	9200
VVR/6	78.75	266	1060574.68	14274
Regenerator	71.25	216.5	863212.10	16600
Dwg. #201860	48	125	226194.67	3500
Dwg. #201861	48	171	309434.31	4300
Dwg. #201862	48	178.75	323458.38	4400
Dwg. #201863	48	124	224385.11	3000
Dwg. #285024	29	40.75	26916.18	700
Dwg. #284137	29	84.09	55543.11	1200
Dwg. #284136	29	66.56	43964.20	950
Dwg. #284135	29	75.53	49889.06	1060
Beam Pipe	13.25	360	49639.13	1650
Final Sweeper	6	72	2035.75	60
Defining Collimator	12	120	13571.68	
Beam Pipe	12	780	88215.92	
NM2 B.P	8	1560	78414.15	
Mu Sweep II	4	240	3015.93	
		141.60 meters	5525.94 ft3	176602. #

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SUBJECT: BUILDING VOL. / VAC VOLUMES

NAME: D. PUSHKA

DATE: 5 DEC 94

REVISION DATE:

NM3 -	118.75' LG	10'-0 WIDE ×	8'-0 HIGH =	9500 FT³
NM3 HATCH	60.08' LG	6'-0 WIDE ×	8'-0 HIGH =	2884 FT³
DECAY	128'-7 LG ×	20'-0 WIDE ×	20'-0 HIGH =	51,433 FT³
HALL	144'-0 LG ×	46'-0 WIDE ×	53'-0 HIGH =	351,072 FT³
				414,889 FT³

GROSS VOLUME =	414,889 FT³	
LESS VACUUM	(6,600) FT³	
LESS SHIELDING	(13,250) FT³	46 × 48 × 6'
LESS BUTTRESSES	(1,721) FT³	5 @ 6'-9 × 17 × 3
LESS MISC	(20,000) FT³	
	373,318 FT³	

$$\Delta P = -(14.32\ \text{PSIA})\left(\frac{552}{373318}\right) = -0.21\ \text{PSI}$$

$$(0.21\ \text{PSI})(144\ \text{IN}^2) = 30.5\ \text{PSF}$$

BLDG WIND LOADING IS NOT LESS THAN 30 PSF
SNOW LOAD IS 25 PSF ON ROOF.

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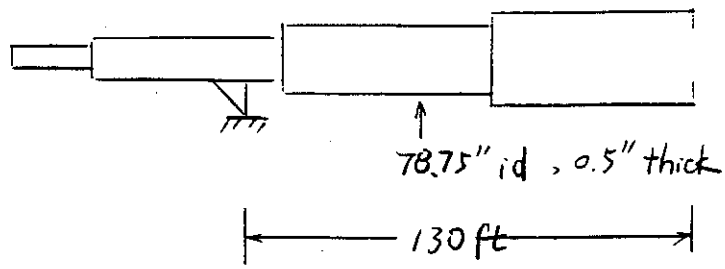
KTeV Vacuum Window Failure Analysis

Zhijing Tang
Jan 16, 1995

This study is about what happens if the vacuum window fails, what is its dynamic effect on vacuum chamber, on SA2 detector, and on the building.

At the time when the vacuum window fails, inside the vacuum chamber, the pressure is zero; while outside is atmosphere pressure. This pressure imbalance will cause dynamic air flow. Air will be sucked into the vacuum chamber until final pressure equilibrium establishs.

Estimate the frequency of the vacuum vessels



$$A = \frac{\pi}{4} t(2d+t) = \frac{\pi}{4}(0.5)(158) = 62.05 \text{ in}^2$$

$$l = 130 \text{ ft} = 1560 \text{ in}$$

$$k_1 = \frac{EA}{l} = 1.193 \times 10^6 \text{ lbf/in}$$

16 triangular legs of height 2ft and made of 3x3x½ angles, the stiffness is calculated as

$$k_2 = 0.4701 \times 16 \times 10^6 = 7.522 \times 10^6 \text{ lbf/in}$$

$$k = (k_1 k_2)/(k_1 + k_2) = 1.030 \times 10^6 \text{ lbf/in}$$

$$\omega = \sqrt{k/m} = \{1.030 \times 385.92/0.176602\}^{1/2}$$

$$= 47.44 \text{ sec}^{-1}$$

$$T = \frac{1}{2\pi\omega} = 3.36 \times 10^{-3} \text{ sec} \ll \tau = 0.45 \text{ sec}$$

From fluid dynamics, the velocity of fluid flow through an openning is given by

$$v^2 = C\,2g_c\,\Delta p/\rho \qquad (1)$$

where $g_c = 32.16$ lbm·ft/sec²·lbf is a conversion factor; $\rho = 0.075$ lbm/ft³ density of air; C is the discharge coefficient, dependent of the shape of the openning. We assume $C = 0.5$.

Substitute into above equation we get

$$v^2 = 61747\,\Delta p \qquad (1.1)$$

where, pressure difference Δp is in psi and velocity v is in ft/sec. With this velocity, the air is sucked into the vacuum chamber.

The mass in the vacuum chamber at the time t after the rupture of the window is

$$m = \int_0^t \rho A v\,dt = 2.06\int_0^t v\,dt \qquad (2)$$

The area of window $A = 3959\ \text{in}^2 = 27.5\ \text{ft}^2$

From the gas equation $pV = nRT$

$$\underbrace{144\,p}_{\text{lbf/ft}^2}\,\underbrace{V}_{5526\ \text{ft}^3} = \frac{m}{\underbrace{29}_{\text{molecular weight}}}\,\underbrace{R}_{1545\ \text{ft-lbf/lbmol-°R}}\,\underbrace{T}_{520°R} \qquad (3)$$

solve for p we get

$$p = 0.0348\, m = 0.0717 \int_0^t v\, dt \qquad (3.1)$$

differentiate gives

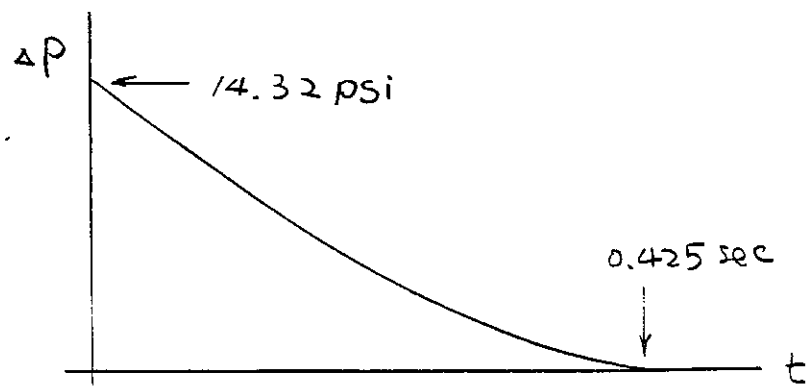
$$\frac{dp}{dt} = -\frac{d}{dt}(\Delta p) = 0.0717\, v = 17.82\sqrt{\Delta p} \qquad (4)$$

integration gives

$$\Delta p = (c - 8.91\, t)^2 \qquad (5)$$

Now at $t=0$, $\Delta p = 14.32$ psi $\Rightarrow c = 3.78$

When $\Delta p = 0$, we have $t_1 = 0.425$ sec



$$\int_0^{t_1} \Delta p\, dt = \frac{14.32^{3/2}}{3 \times 8.91} = 2.027 \text{ psi-sec}$$

maximum force $\Delta p \cdot A = 56700$ lbf

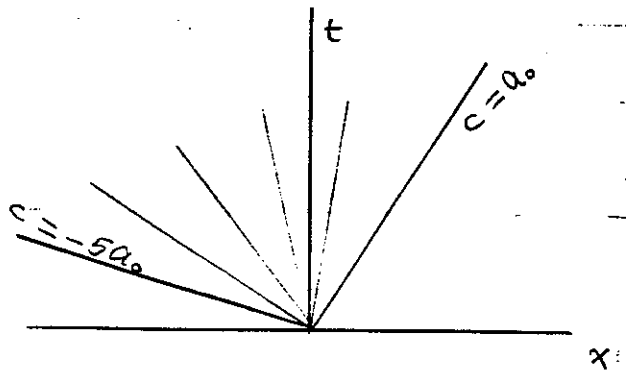
impulse length $t_1 = 0.425$ sec

total momentum $A \int \Delta p\, dt = 8026$ lbf-sec

Average force $A \int \Delta p\, dt / t_1 = 18885$ lbf

From 1 dimensional wave theory, if we neglect the reflected waves, the solution is self-similar. that is, all variables are functions of $c = x/t$ (we assume the position of the vacuum window as $x=0$)

The whole solution domain can be divided into three regions.



the region under $c=a_0$ is a constant region with atmosphere pressure; the region under $c=-5a_0$ is also a constant region with vacuum; the region in between is a simple solution region where

$$a = \frac{1}{6}(c + 5a_0) \tag{6}$$

$$v = \frac{5}{6}(c - a_0) \tag{7}$$

$$\rho = \frac{a^5}{23.45 \times 10^{15}} \tag{8}$$

$$p = \frac{a^7}{0.1520 \times 10^{21}} \tag{9}$$

a — speed of sound, a_0 — speed of sound under atmospheric pressure, v — flow velocity. ρ — density. p — pressure.

At $x=0$, we have $c=0$ and

$$a = \frac{5}{6} a_0 = 1008, \quad v = -\frac{5}{6} a_0 = -1008, \quad a_0 = 1210 \text{ ft/sec}$$

$$\rho = 0.04445 \text{ lbm/ft}^3$$

The time t_2 required to fill the vacuum chamber can be estimated by following equation

$$\rho_0 V = -A v \rho t \tag{10}$$

$$t_2 = \frac{\rho_0 V}{-A v \rho} = \frac{0.075 \times 5526}{27.5 \times 1008 \times 0.04445}$$

$$= 0.336 \text{ sec}$$

Remember in equation (1) we introduced a discharge coefficient $C = 0.5$ to take into account of viscoucity. By this, the flow velocity reduces by a factor of $1/\sqrt{2}$. Similarly if we introduce a factor here, the time required to fill the vacuum vessels will be larger than that predicted by eqn (10)

$$t_2^* = \sqrt{2}\, t_2 = 0.476 \text{ sec}$$

This is consistent with t_1 estimated from eqn (5). If we take average of t_1 and t_2^* as our estimated time to fill the vacuum

chamber, then

$$\tau = (t_1 + t_2^*)/2 = 0.45 \text{ sec}$$

Now we have following parameters for the load on the vacuum vessels

maximum load = 56700 lbf
Impulse length = 0.45 sec
Impact momentum = 8026 lbf-sec
Average load = 17836 lbf

Since the impulse length is 134 times larger than the characteristic time of the vacuum vessel structure, the load can be treated as static.

maximum deflection

$$\delta = F/k = 56700/1.030\times10^6 = \underline{0.055 \text{ in}}$$

maximum load on each of the legs

$$f = F/16 = 3544 \text{ lbf}$$

This will result in a stress of

$$\sigma = 3544\sqrt{2}/1.44 = \underline{3480 \text{ psi}}$$

It is assumed that the drifting chamber DC1 and the helium bags will be totally destroyed when the vacuum window breaks. Some load will then be applied to SA2.

From the 1-d wave solution, the pressure on SA2 will be about 4.06 psi. On the other side of SA2 the pressure is 14.32 psi, that gives a pressure difference of $\Delta p = 10.26$ psi.

This is based on the one-dimensional flow assumption. Actually, air will be sucked in from all the directions. We assume the effective area is a 20 ft radius hemisphere $A = 2\pi r^2 = 2513\ ft^2$ instead of $27.5\ ft^2$. then the estimated load will be

$$\Delta p = 10.26 \frac{27.5}{2513} = 0.1123 \text{ psi}$$

The dimension of SA2 is

$$4310 \times 4581 - 1548 \times 1366 = 17629542\ mm^2$$
$$= 27326\ in^2$$

so the maximum load on SA2 is

$$0.1123 \times 27326 = 3068 \text{ lbf}$$

Compare with weight of SA2 which is about 10000 lbf.

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SUBJECT	NAME	DATE	REVISION DATE
LOADS APPLIED TO SA2 A-FRAME	DAVE PUSHKA	10 FEB '95	

FROM SECTION 4.0 (PAGE 10), ZHIJING CALCULATES A 3069 LBf LOAD APPLIED TO SA2. GEOMETRY IMPLIES THAT THIS FORCE SHOULD BE APPLIED TO THE BEAM ℄.

THEREFORE, APPROXIMATELY $\frac{3069}{4}$ LBf (770#) ARE APPLIED TO EACH OF THE FOUR CORNERS OF SA2.

EACH SIDE OF THE A-FRAME IS DESIGNED FOR A 1200 (1.2 KIP) LOAD @ THE TOP. THIS EXCEEDS THE 770# LOAD (SEE THE A-FRAME ENGR NOTE MSD-EN 1.1.3.8-KTeV DATED 16 DEC '94 BY D. PUSHKA). THE LOWER CORNERS USE CLIPS DESIGNED FOR 1100#'S (SEE THE SA4, CH4, TRD, DC4 & TRIGGER HODOSCOPE SUPPORT DESIGN NOTE BY D. PUSHKA DATED 30 JULY '94). THIS EXCEEDS THE 770 # LOAD. BUT THIS NEEDS TO BE ADDED TO A-FRAME.

$\therefore \frac{3069}{2} = 1535$# APPLIED 8" ABOVE T.O.C TO A-FRAME IS THE EQ LOAD DUE TO $\frac{(1535)(8)(12)}{172.75_{IN}} = 853$ #
(A-FRAME HEIGHT = 172.75")

APPLIED TO TOP. 853 < 1,200 # ∴ A-FRAME IS SUFFICIENT TO TAKE LOAD ON SA-2 DUE TO A WINDOW FAILURE

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WEIGHT VS VOLUMN COMPARISON	DAVE PUSHKAR	6 DEC '94	

WINDOW TEST TABLE:

VOL = 30.7 FT^3

WT = 4250 #

RATIO = 30.7/4250 = 7.2×10^{-3} $\frac{FT^3}{\#}$

KTeV ASSEMBLED SYSTEM:

VOL = 5526 FT^3

WT = 176,602 #

RATIO = 5526/176,602 = 3.1×10^{-2} $\frac{FT^3}{\#}$

$$\frac{3.1 \times 10^{-2}}{7.2 \times 10^{-3}} = 4.33$$

THEREFORE, THE KTEV VACUUM HAS A FACTOR OF 4.3 HIGHER VOLUMN TO WIEGHT RATIO THAN DOES THE TEST TABLE.

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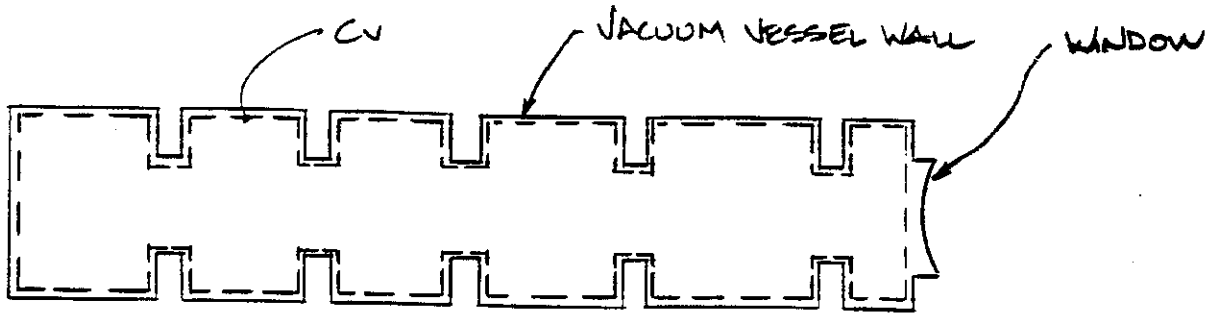
SUBJECT: VACUUM VESSELS - STORED ENERGY

NAME: DANE POSHKA

DATE: 7 DEC '94 | REVISION DATE

GIVEN:



BASIC EQN:

$$\underbrace{\cancel{Q}}_{0\ (1)} - \underbrace{\cancel{W_{SHAFT}}}_{0\ (2)} + \underbrace{\cancel{W_{BOUNDARY}}}_{0\ (3)} + \int (e + Pv)\, dm = \Delta E_{CV}$$

ASSUMPTIONS:

(1) ADIABATIC
(2) NO SHAFT WORK
(3) NO CHANGE IN CV

$$\underbrace{\cancel{Q}}_{0} + \underbrace{\cancel{W_{SHAFT}}}_{0} + \underbrace{\cancel{W_{BDRY}}}_{0} + \int (e + Pv)\, dm = \Delta E_{CV}$$

& BOUNDRY WORK $= W'_{BNDRY} = -P(V_f - V_i)$

$$\underbrace{-P(\cancel{V_f - V_i})}_{0} + \int h\, dm = m_f u_f - m_i u_i$$

(PG 386 WARK)

& $h \equiv u + Pv \quad \therefore Pv = h - u$ (PG 62 WARK)

ASSUME $m_i = 0$ SINCE THE CV IS INITIALLY FULLY EVACUATED.

$$m_f = \frac{P_f V}{RT} = \frac{(14.32\ \text{PSIA})(5526\ \text{FT}^3)(29)}{\left(10.73\ \frac{\text{PSIA-FT}^3}{\#\ \text{MOL}\ ^\circ R}\right)(520\ ^\circ R)} = 411\ \text{lb}_m$$

@ $T = 520^\circ R$ ($60^\circ F$) $u = 88.62\ \frac{\text{BTU}}{\text{lb}_m}$, $h = 124.27\ \frac{\text{BTU}}{\text{lb}_m}$

$\therefore$ THE PV WORK IS $\Delta E_{PV} = (\Delta h - \Delta u)\, m_f$

$$= \left(124.27\ \frac{\text{BTU}}{\text{lb}_m} - 88.62\ \frac{\text{BTU}}{\text{LBM}}\right)(411\ \text{lb}_m)$$

$$= 14{,}652\ \text{BTU}$$

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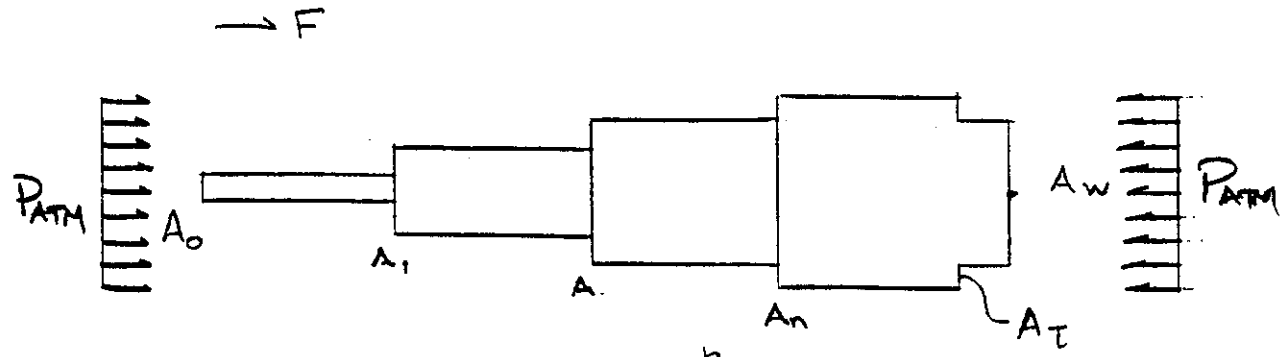
FREE BODY DIA. OF VAC. SYSTEM @ $t = 0^+$	D. PUSHKA	5 DEC '94	



WHILE UNDER VACUUM, $P_{ATM}\ \text{PSIA}\left(\sum_{m=0}^{n} A_m\right) = P_{ATM}\ \text{PSIA}\left(A_T + A_W\right)$

$$A_W = \frac{\pi}{4}(71^2) = 3959\ \text{in}^2$$

$$A_T = \frac{\pi}{4}(94.5^2 - 71^2) = 3054\ \text{in}^2$$

$$\therefore \sum_{m=0}^{n} A_m = A_W + A_T = 3959 + 3054 = 7013\ \text{in}^2$$

AT THE INSTANT THE WINDOW BREAKS, THE NET FORCE ON THE VACUUM VESSEL IS:

$$F + P_{ATM}(7013\ \text{in}^2) = P_{ATM}(3054)$$

$$F = -P_{ATM}(+7013 - 3054) = -3959\ P_{ATM}$$

P_{ATM} @ 750' ELEV IS 14.32 PSIA

$$\therefore F = 56{,}700\ \#$$

USE 57 KIPS

FOR AN ASSUMED ALLOWABLE SHEAR OF 12 KSI, 4.75 in^2 OF MAT'L IS REQD IF LOAD DURATION IS IGNORED AND SYSTEM CONSIDERED STEADY STATE. (THIS WOULD BE A <u>GROSS</u> SIMPLIFICATION).

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