REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

AD-A281 313

2. REPORT DATE
June 1994

3. REPORT TYPE AND DATES COVERED
Professional Paper

A QUASI-SINGLE MODE OPTICAL FIBER FOR LONG-HAUL TRANSMISSION IN SEVERE BENDING ENVIRONMENTS

5. FUNDING NUMBERS
PR: ZE 93
PE: 0602936N
WU: DN300043

6. AUTHOR(S)
N. Kamikawa and C. Chang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152-5001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Chief of Naval Research
OCNR-20T
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DTIC
ELECTE
JUL 07 1994
S G D

94-20618

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

88

13. ABSTRACT *(Maximum 200 words)*

We investigated the feasibility of a quasi-single mode optical fiber for low bending losses in long-haul transmission at 1550 nm. The advantage of a quasi-single mode fiber is that for comparable bending losses the relative index difference, Δ, can be smaller than the Δ in a single-mode fiber. We demonstrated that a quasi-single mode fiber with $\Delta = 0.72\%$ and single-mode cutoff wavelength, λ_c, equal to 1630 nm exhibits bending losses as low as the losses in a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm. Modal noise and modal dispersion effects in the quasi-single mode fiber also were tested and found to be minimal. This paper describes the matched-clad, quasi-single mode fiber and presents the test results.

DTIC QUALITY INSPECTED 3

Published in *IEEE Photonics Technology Letters*, vol. 6, no. 3, pp. 428–430, March 1994.

14. SUBJECT TERMS
cutoff wavelength
dispersion
fiber optics
microbending loss
mode coupling

15. NUMBER OF PAGES

16. PRICE CODE

94 7 6 076

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

UNCLASSIFIED

21a. NAME OF RESPONSIBLE INDIVIDUAL N. Kamikawa	21b. TELEPHONE *(include Area Code)* (808) 257-1165	21c OFFICE SYMBOL Code 534

2 May 1994

MEMORANDUM

Lillian
open lit
dbase
& to DTIC

From: Neil Kamikawa, Code 4204
To: Head, Code 027

Subj: SF292 FOR DEFENSE TECHNICAL INFORMATION CENTER (DTIC)

Ref (a) Navy Case # 73,514

Encl: (1) "A Quasi-Single Mode Optical Fiber ..."
(2) Code 961 memo

1. Encl. (1) has been published in the Photonics Technology Letters, which is a peer-reviewed journal of the IEEE. I have completed Encl. (2) for submission of an SF292 to DTIC.

2. The work reported in Encl. (1) was performed while I was a member of Code 534. It was supported by the Center's IED program in FY90, and by the Office of Advanced Technology in FY91. A U.S. Patent (Ref. (a)) was issued on 11 April for the invention described in Encl. (1).

3. If you need more information, I can be reached via e-mail at kamikawa@humu.

Neil Kamikawa
Neil Kamikawa

Copy to:
Dr. S.B. Schneiderman, Head, Code 4204
Dr. K. Campbell, Code 0142
T. Keough, Code 0012
D. Murphy, Head, Code 53

Accesion For	
NTIS CRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and / or Special
A-1	

A Quasi-single Mode Optical Fiber for Long-Haul Transmission in Severe Bending Environments

Neil Kamikawa, *Member, IEEE*, and Ching-Ten Chang, *Member, IEEE*

***Abstract*—We investigated the feasibility of a quasi-single mode optical fiber for low bending losses in long-haul transmission at 1550 nm. The advantage of a quasi-single mode fiber is that for comparable bending losses the relative index difference, Δ, can be smaller than the Δ in a single-mode fiber. We demonstrated that a quasi-single mode fiber with $\Delta = 0.72\%$ and single-mode cutoff wavelength, λ_c, equal to 1630 nm exhibits bending losses as low as the losses in a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm. Modal noise and modal dispersion effects in the quasi-single mode fiber also were tested and found to be minimal. This letter describes the matched-clad, quasi-single mode fiber and presents the test results.**

I. INTRODUCTION

WE INVESTIGATED techniques to reduce both bending losses and spectral attenuation in an optical fiber to increase transmission distances at 1550 nm in applications where the fiber is severely bent with bending radii of several mm. Our approach is to combine a pure-silica core fiber for spectral attenuation reduction with quasi-single mode operation for bending loss reduction. We achieved an intermediate goal in which a quasi-single mode fiber was realized in a matched-clad design to study bending loss, modal noise, and modal dispersion. The matched-clad, quasi-single mode fiber with $\Delta = 0.72\%$ and $\lambda_c = 1630$ nm exhibits low bending losses that are comparable to a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm, but the smaller Δ in the quasi-single mode fiber permits the future fabrication of the quasi-single mode specification in a depressed-clad, pure-silica core design. The largest Δ reported in a pure-silica core fiber is 0.73% [1].

The high λ_c in the quasi-single mode fiber has the same effect in reducing bending losses as the high Δ in the single-mode fiber. This is demonstrated in bending tests and is in agreement with measured guided-wave phase indexes and refractive-index profiles. With λ_c of 1630 nm > 1550 nm, both the LP_{01} and LP_{11} modes may propagate and may penalize the transmission link via modal noise and multimode modal dispersion. We found that at 200 MB/sec the modal noise penalty is ≤ 0.3 dB, and determined that there is no modal dispersion since the spectral attenuation of the LP_{11} mode is about three orders of magnitude greater than the attenuation of the LP_{01} mode at 1550 nm. The small modal effects also are consistent with our guided-wave phase-index measurements which show that mode coupling is small and that the LP_{11} mode is barely guided.

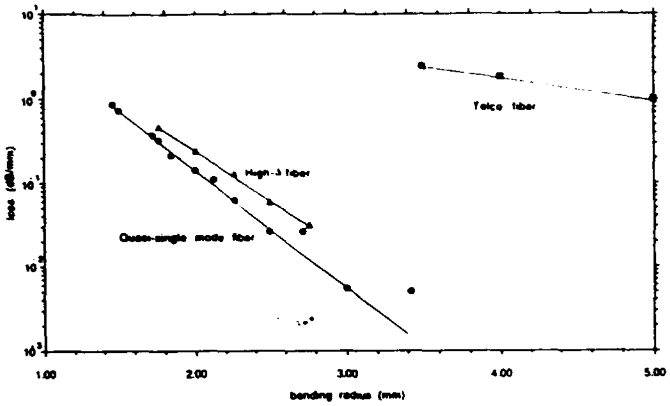


Fig. 1. Measured bending losses at 1550 nm.

This letter describes the matched-clad, quasi-single mode fiber and discusses the results of bending, guided-wave phase-index, modal noise, and spectral attenuation tests.

II. FIBER DESCRIPTION

The performance goal for the matched-clad, quasi-single mode fiber was to achieve very low bending losses similar to bending losses in a high-Δ, single-mode fiber [2], [3] described in Table I. Further, the quasi-single mode fiber should have a $\Delta \leq 0.73\%$, the largest Δ reported for a pure-silica core fiber [1], to allow future implementation of the fiber in a pure-silica core design. The quasi-single mode fiber described in Table I meets these requirements. The fiber's measured bending losses are nearly equal to that in the high-Δ fiber, as shown in Fig. 1, and its Δ is 0.72%.

The nearly equal bending losses can be explained using a single-mode step-index model with core radius, a, core index, n_1, and cladding index, n_2. The propagation constant of the guided optical wave is constrained by $n_2k \leq nk \leq n_1k$, where $k = 2\pi/\lambda$, the free-space propagation constant, and n is the guided-wave phase index. In a bend of radius R, the LP_{01} mode field amplitude-loss coefficient, α, in Nepers/mm is given in [4] and its corresponding optical power-loss coefficient $\alpha_c (= 8.68\alpha)$ in dB/mm is

$$\alpha_c = \frac{8.68}{4}\sqrt{\frac{\pi k}{R}}\frac{(n_1^2 - n^2)\exp[-2(n^2 - n_2^2)^{3/2}kR/3n^2]}{(n^2 - n_2^2)^{3/2}(ka\sqrt{n_1^2 - n_2^2})^2 K_1^2(ka\sqrt{n^2 - n_2^2})}. \tag{1}$$

Manuscript received November 16, 1993.

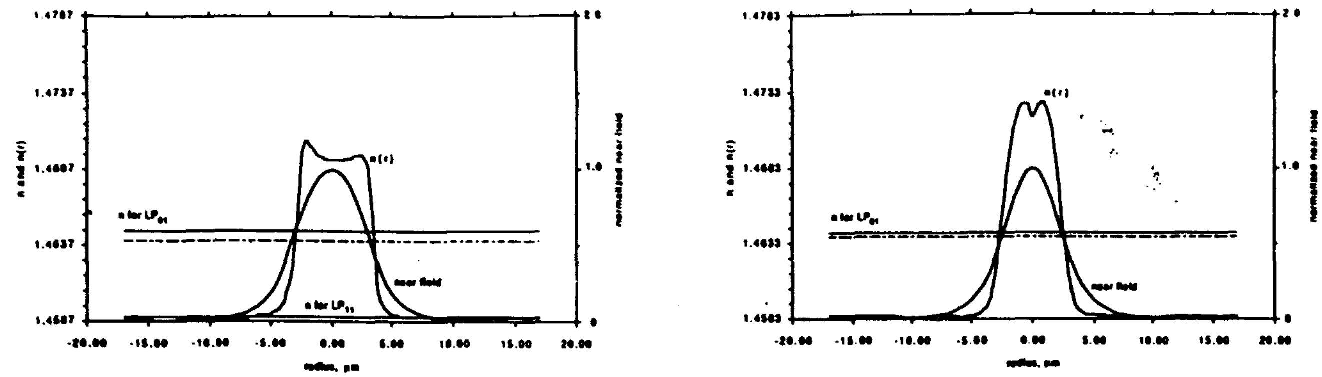
Naval Command, Control and Ocean Surveillance Center, Research, Development, Test & Evaluation Division, Box 250, Pearl Harbor, Hawaii 96860-5290.

San Diego State University, Department of Electrical and Computer Engineering, San Diego, CA 92182-0190.

IEEE Log Number 9216586.

1041-1135/94$04.00 © 1994 IEEE

Enclosure (1)



(a) quasi-single mode fiber

(b) high-Δ fiber

Fig. 2. Refractive-index profile $n(r)$, near field, and calculated (solid horizontal line) and measured (dashed horizontal line) phase index n at 1550 nm. (a) quasi-single mode fiber. (b) high-Δ fiber.

TABLE I
FIBER SPECIFICATIONS

Fiber	λ_c	n_1	n_2	Δ	ω_{∞}	ω_0	n for LP_{01} (measured)	n for LP_{01} (calculated)	n for LP_{11} (measured)
	nm			%	µm	µm			
Quasi -single mode	1630	1.4692	1.4587	0.72	3.97	3.96	1.4640	1.4646	1.4590
High Δ	1259	1.4721	1.4585	0.93	4.01	3.53	1.4637	1.4640	
Telco	1154	1.4635	01.4585	0.36	6.40	5.39	1.4605	1.4602	

λ_c is the cutoff wavelength, n_1 is the core index, n_2 is the cladding index, Δ equals $(n_1-n_2)/n_2$, ω_{∞} is the cladding-field decay constant, ω_0 is the rms mode-field radius, and n is the guided-wave phase index.

where K_1 is the modified Hankel function of first order. The guided-wave phase index, n, in (1) can be obtained by solving the characteristic equation [5], [6] or by measuring the near and far fields [7]. According to (1), the theoretical bending losses in both the quasi-single mode fiber and high-Δ fiber are about 1.5 dB/mm for a 2-mm radius bend.

III. TEST RESULTS AND DISCUSSION

As shown in Fig. 1, the measured bending losses in the quasi-single mode fiber at 1550 nm are comparable to losses in the high-Δ fiber and are much less than losses in a typical telco fiber that was tested for comparison. The measured loss in the quasi-single mode fiber at $R = 2.0$ mm is 0.15 dB/mm but (1) predicts a loss of 1.5 dB/mm, assuming a step-index profile. The lower measured loss can be explained by the non-step refractive index profile with the small central index depression [8], as shown in Fig. 2. Small radius bends cause the peak of the near field to shift outward from the central index depression toward the off-center index maximum at the core-clad interface. The off-center index maximum reduces the degradation of the mode confinement caused by the bend, which reduces the bending loss to less than that predicted by (1).

For a given R and k, the LP_{01} mode bending loss is mainly determined by the exponential term and the Hankel function term in (1). These two terms in turn depend on $n^2 - n_2^2$ which is proportional to $n - n_2$ for the weakly-guided fibers in Table I. A larger $n - n_2$ indicates stronger optical confinement and reduces bending losses. Our experimentally derived $n - n_2$ values are approximately the same for the quasi-single mode fiber and the high-Δ fiber. The strong optical confinement in the former fiber is due to longer λ_c (or larger core diameter) as shown in Fig. 2(a), while the strong optical confinement in the latter fiber is due to the large Δ as shown in Fig. 2(b).

Our estimations of n are believed to be reliable since measured and calculated n are nearly the same in each fiber, as shown in Fig. 2 and Table I. The measured n is based upon the near-field measurement to estimate the LP_{01} mode phase index as $n \approx \left(\frac{2}{k^2 n_2 \omega_{\infty}^2}\right) + n_2$. Here, Petermann's cladding-field decay constant, ω_{∞} [7], is obtained by fitting the expression $E(r) \propto \left(\frac{1}{\sqrt{r}}\right) \exp\left(\frac{-2r}{\omega_{\infty}}\right)$ to the measured near field in the cladding. The near fields were obtained by taking the inverse Hankel transformation of the far fields measured at 1550 nm. Fig. 3 shows the measured and fitted near fields. The calculated n is based upon the expression $n = \sqrt{b(n_1^2 - n_2^2) + n_2^2}$, where b is the normalized propagation constant. By measuring λ_c, the normalized frequency $V = 2.405\left(\frac{\lambda_c}{\lambda}\right)$ is estimated and used to obtain b by solving the LP_{01} mode characteristic equation [5], [6].

The λ_c were measured using the multimode reference technique and the refractive indexes were measured with the refractive near-field method. The root-mean-square mode-field radii, ω_0, also were measured as shown in Table I. It is interesting to note that the high-Δ fiber exhibits a smaller ω_0 but the bending losses in the both fibers are similar, suggesting that ω_0 is not a good predictor of bending losses in fibers of dissimilar refractive-index profiles.

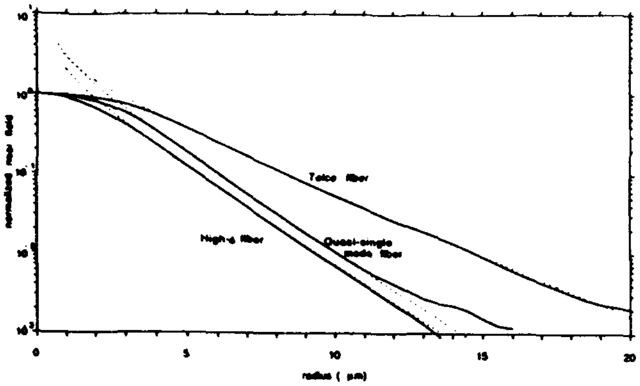


Fig. 3. Measured near fields at 1550 nm (solid line) and curve fit to near field in cladding (dashed line).

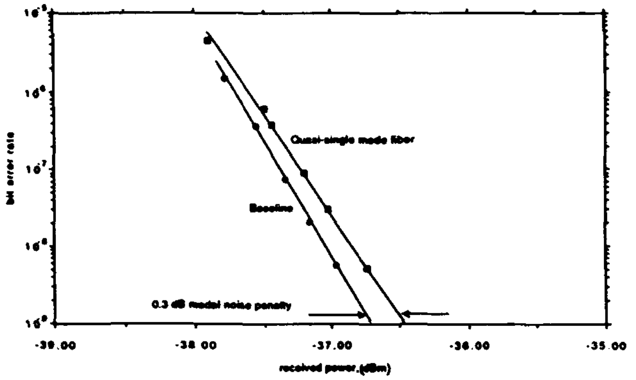


Fig. 4. Bit-error rate measured at 200Mb/s.

Since the quasi-single mode fiber supports both the LP_{01} and second-order LP_{11} modes modal noise and modal dispersion can impact system performance. To determine the impact of modal noise bit-error rates were measured on a 2.1-km length of the quasi-single mode fiber at a data rate of 200 Mb/s and a pseudo-random bit sequence length of $2^{20} - 1$. A misaligned splice characterized by a 1.5-dB loss was inserted 2 meters from the end of the fiber that was terminated in a connector and attached to a pigtailed PINFET receiver to create a worse-case situation for modal noise. However, the modal noise power penalty was only about 0.3 dB, as shown in Fig. 4, with respect to a baseline measurement made by removing the quasi-single mode fiber and connecting the laser transmitter pigtail directly to the PINFET receiver pigtail. The large difference between the n for the LP_{01} mode and the n for LP_{11} mode in the quasi-single mode fiber indicates that mode coupling is small and supports the low modal noise penalty test result.

The spectral attenuation of the modes at 1550 nm were measured using a cutback technique [9] to indirectly evaluate modal dispersion since long lengths of the quasi-single mode fiber were not available for direct dispersion measurements. The LP_{11} mode exhibited an attenuation three orders of magnitude greater than the attenuation of 0.3 dB/km for the LP_{01} mode to preclude modal dispersion. The very high attenuation in the LP_{11} mode is consistent with the n measurement. Fig. 2(a) shows that n for the LP_{11} mode is very close to n_2 indicating that the mode is barely guided.

IV. SUMMARY

Bending loss, modal noise, and spectral attenuation tests supported by guided-wave phase-index measurements show that quasi-single mode fibers are feasible for reduced bending losses in long-haul transmission in severe bending environments. Reducing bending loss by increasing the core radius to increase optical confinement of the guided wave in a quasi-single mode fiber is comparable to increasing the relative index difference in a high-Δ fiber. The feasibility of a quasi-single mode fiber for low bending loss at 1550 nm has been established, with a potential for implementation in a depressed cladding and pure-silica core to minimize Rayleigh-scattering loss.

ACKNOWLEDGMENT

This work was supported by the Independent Exploratory Development program at the Naval Command, Control and Ocean Surveillance Center, RDT&E Division. The quasi-single mode fiber was fabricated by Ensign-Bickford Optical Technologies.

REFERENCES

[1] A. Urano, Y. Ishiguro and M. Shigematsu, et. al., "Pure silica core dispersion-shifted single-sode sibers," *Proc. 13th ECOC*, pp. 175–178, Sept. 1987.
[2] T. C. Starkey and J. W. Suggs, "Reduced mode-field diameter single-mode fiber for specialty applications," *Proc. IW&CS*, pp. 15–17, Nov. 15–17, 1988.
[3] M. W. Shute and H. T. Shang, "Optical fibers for tethered vehicle applications," *DoD Fiber Optics Conf.*, pp. 187–191, Mar. 20–23, 1990.
[4] D. Marcuse, "Curvature loss formula for optical fibers," *J. Opt. Soc. Amer.*, vol. 66, pp. 216–220, 1976.
[5] D. Gloge, "Weakly guiding fibers," *Appl. Opt.*, vol. 10, pp. 2252–2258, 1971.
[6] C. T. Chang, "Minimizing dispersion in a single-mode step-index fiber," *Appl. Opt.*, vol. 18, pp. 2516–2522, 1979.
[7] K. Petermann, "Mode-field characteristics of single-mode fiber designs," *Tech. Digest OFC/IOOC*, paper TuA1, Jan. 19–22, 1987.
[8] N. Kamikawa and C.-T. Chang, "Losses in small-radius bends in single-mode fibers," *Electron. Lett.*, vol. 25, pp. 947–949, 1989.
[9] M. Ohashi, K. Kitayama, T. Kobayashi and Y. Ishida, "LP_{11} mode loss measurements in the two-mode propagation region of optical fibers," *Opt. Lett.*, vol. 9, pp. 303–305, 1984.

01/05/93

RECEIVED 2/3/93

MEMORANDUM

From: Code 961
To: Kamikawa, N., Code 534

Subj: PROFESSIONAL PAPERS AND PRESENTATIONS

Ref: (a) Unclassified Technical Information Release 92050

1. Center records indicate you submitted the following for publication or presentation:

A Dual-Mode Optical Fiber for Long-Haul Transmission at 1550 nm

Reference (a) indicates that the paper or presentation may be published in Electronics Letters.

2. Was the article accepted for publication?

✓ Yes ____ No ____ Information not yet available

If "yes" please provide the following information:
Title of journal IEEE Photonics Technology Letters
Volume, issue, and date of Journal or Proceedings Vol. 6, No. 3, March 1994
Page numbers 428-430
Job order used to perform work ZE93

3. This information will enable Code 961 to prepare an SF292 for the Defense Technical Information Center (DTIC). Your response ensures NRaD's recognition for work published in other than the NRaD formal publication series. This information also helps prepare lists of Publications for the IR/IED report and helps the NRaD Technical Library prepare lists of references by NRaD authors.

4. A job order is not required for us to do this work. However, we'd appreciate receiving 1 to 3 copies of your published paper, presentation, or abstract.

5. If you have any questions, please call Juni Jodzio, extension 34795, or email juni.

LCDR Larry Ledford

Enclosure (2)

NOSCINST 5720.2A

UNCLASSIFIED 92 050

UNCLASSIFIED TECHNICAL INFORMATION RELEASE

See instructions on back for completeing this form.
Submit one copy of material with one copy of this form.

FROM	EXT	CODE	DATE CLEARANCE NEEDED
Neil Kamikawa	(808)-257-1165	534	1/31/92

1. Release is requested for the attached material. This paper is related to NOSC Project No. ZE93

The following systems commands/sponsor codes are cognizant: ONT

2. THE SPONSOR IS AWARE OF AND HAS APPROVED THIS RELEASE. ☑ YES ☐ NO

TITLE OF MATERIAL

A Dual-Mode Optical Fiber for Long-Haul Transmission at 1550 nm.

TYPE OF RELEASE

☑ PROFESSIONAL PAPER ☐ CONTRACTOR RELEASE ☐ PRESENTATION/ SPEECH ☐ BROCHURE ☐ OTHER TYPE PUBLICATION OR RELEASE

MEETING *(If presentation or speech)*	PLACE AND DATE OF MEETING

NAME OF PUBLICATION *(If applicable)*

Electronics Letters

3. It is my opinion that the subject matter in this material has no information or military application requiring classification.
4. To the best of my knowledge, this material does not disclose any trade secrets or suggestions of outside individuals or concerns which have been communicated to NOSC in confidence.
5. THIS MATERIAL ☐ DOES ☑ DOES NOT INCLUDE MILITARILY CRITICAL TECHNOLOGY. *(NOSCINST 5510.4)*
6. DISTRIBUTION STATEMENT A IS RECOMMENDED. *(See reverse)*

SIGNATURE (Author's) Neil T. Kamikawa DATE 1/3/92

Signature below certifies that this material has been reviewed for security, appropriate distribution statement, proprietary information, and infringement on contractor work.

			CODE	DATE
SIGNATURE *(Branch, Project, or Group Head)*			534	1/22/92
Contains Military Critical Technology ☐ Yes ☒ No	DISTRIBUTION STATEMENT A IS RECOMMENDED. *(See reverse)*	SIGNATURE *(Division, Project or Group Head)*	53	1/22/92
SIGNATURE *(Legal Counsel for Patents)* REVIEWED FOR PATENTABLE SUBJECT MATTER Thomas Glenn Keough			0012	30 Jan 92
SIGNATURE *(Information Security Group)*	DISTRIBUTION STATEMENT A IS RECOMMENDED. *(See reverse)*		152	2-3-92
SIGNATURE *(Public Affairs Officer)** T J La Puzza			032	2/6/92

COMMENTS

ET AL GRANT TANAKA
SAN DIEGO STATE UNIVERSITY

1/52

*NOTE: To avoid premature disclosure of unclassified patentable technology with high commercial potential, the Technology Transfer Coordinator will receive copies of completed route sheets for review.

(Public Affairs will route to Technology Transfer Coordinator)

DISTRIBUTION STATEMENT A IS ASSIGNED.	SIGNATURE T J La Puzza *(By direction of the Commander)*	DATE 2/6/92

All previous editions are obsolete