"**On the Scientific Viability of a Restructured CRAF Science Payload**"

On August 10, 1990, Dr. Larry W. Esposito, chair of the Committee on Planetary and Lunar Exploration, and Dr. Louis J. Lanzerotti, chair of the Space Studies Board, sent the following letter to Dr. Lennard A. Fisk, associate administrator for NASA's Office of Space Science and Applications.

In response to cost growth in the Comet Rendezvous Asteroid Flyby (CRAF) program and insufficient reserves for fiscal years 1991 and 1992, you requested that the Space Studies Board assess the scientific viability of a restructured CRAF science payload. Your letter of 2 July 1990 to the SSB Chairman, Louis J. Lanzerotti, indicated that NASA would propose several options for descoping the CRAF mission and requested the Board's Committee on Planetary and Lunar Exploration (COMPLEX) to

1. identify the impacts which each option would have on meeting the scientific objectives for the study of primitive bodies;
2. assess the overall viability of each payload option in terms of its ability to contribute successfully to implementation of the committee's science strategy; and
3. determine whether any of the descoping options appear so severe as to leave the CRAF project unresponsive to COMPLEX's scientific strategy for the exploration of primitive bodies.

The Board's responding letter of 9 July 1990 indicated that it was requesting COMPLEX to review the descoping options proposed by NASA and also to explore additional options, together with related issues, that might preserve acceptable combinations of the primary scientific objectives for CRAF. COMPLEX accepted this larger task, of which the assessment of options proposed by the CRAF Project science Group (PSG) can now be considered a subset. In addition to evaluating the proposed options, COMPLEX has considered all the experiments on the baseline CRAF mission both individually and in groups for their responsiveness to the Committee's existing scientific strategy for the study of primitive bodies in the solar system.

CRAF is a mission designed to meet the highest scientific objectives for the study of comets and asteroids. The baseline payload has been judged by COMPLEX to be fully responsive to these scientific objectives. The CRAF mission has been combined programmatically with the Cassini (Saturn Orbiter/Titan Probe) mission, whose mutual objective has been described as "understanding the birth and evolution of our planetary system." CRAF is the first U.S. spacecraft mission dedicated primarily to the study of primitive bodies and is thus important in maintaining a balanced approach to exploration of the various elements central to the evolution of the solar system, as described in previous Space Studies Board and COMPLEX reports.

Two general points should be made about this review. The first is that scientific objectives for the study of asteroids do not figure strongly in the evaluation of CRAF. Although the asteroid flyby is a significant part of the mission and was discussed by the Committee in its deliberations, the matters related to the scientific objectives for the study of asteroids were not as strong in determining the scientific return of the mission because the majority of the mission duration and effort is directed toward the comet rendezvous. Secondly, COMPLEX noted that since the CRAF mission is a part of the combined CRAF/Cassini program, the scientific evaluations would be conducted in the absence of direct information about the Cassini scientific capabilities because the Cassini payload has not yet been selected. Therefore, in light of the many commonalities between CRAF and Cassini, this evaluation must be considered incomplete. The NASA program managers for CRAF have assured the Committee, however, that CRAF science will not be compromised in favor of Cassini, nor vice versa.

COMPLEX met on 12-13 July 1990 to hear presentations by personnel from NASA headquarters and from the Jet Propulsion Laboratory's (JPL) CRAF Project. These presentations outlined the background and the magnitude of the CRAF cost overrun. The presenters identified and discussed with the Committee the actions planned to reduce and spread out costs for the other major elements of the mission, including the spacecraft. The remaining budgetary difficulties were found to require some descoping of the science payload. COMPLEX was consequently provided with two options developed by the PSG for descoping the science payload (see Appendix A). Option 1 was a deletion of the CRAF penetrator and its suite of instruments. Option 2 consisted of a specific list of descoping options, whose total cost savings in FY91 and FY92 would still leave a substantial shortfall. This option also included another list of cost savings that could be achieved by deleting entire instruments. No priority among these instruments was presented to COMPLEX.

The scientific impacts of these options for descoping were evaluated against the scientific objectives identified by COMPLEX in its report, *Strategy for the Exploration of Primitive Solar-System Bodies: Asteroids, Comets and Meteoroids: 1980-1990* (National Academy of Sciences, 1980), and as discussed in three subsequent letter reports (dated 31 May 1985, 27 May 1987, and 1 September 1988). The Committee's primary objectives for comet exploration, established in the 1980 strategy in order of priority, are

1. to determine the composition and physical state of the nucleus

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(determination of the composition of both dust and gas is an important element of this objective);
2. to determine the processes that govern the composition and distribution of neutral and ionized species in the cometary atmosphere; and
3. to investigate the interaction between the solar wind and the cometary atmosphere. (p. 28)

Based on a comparison of the two proposed options with these objectives, COMPLEX does not recommend either option. Instead, the Committee has developed a third option as described below.

COMPLEX recommends that CRAF's budgetary shortfall be met by the following actions: (1) cap the Penetrator-Lander (PENL) experiment's costs in FY91 and FY92. as proposed by the experiment's Principal investigator; (2) delete the PENL's heat shield cover; and (3) delete from the selected mission payload the Scanning Electron Microscope and Particle Analyzer (SEMPA), the Magnetometer (MAG), the Coordinated Radio, Electron, and Wave Experiment (CREWE), and the Cometary Retarding Ion Mass Spectrometer (CRIMS) instruments. In arriving at this recommendation COMPLEX was guided by the belief that more science would be lost by making extensive cuts spread throughout the whole instrument package than by selectively removing a few instruments. Selecting which experiments to delete was of course difficult, because all the experiments have the potential to yield unique and important information.

In making this recommendation, COMPLEX compared all the CRAF instruments' anticipated capabilities to the Committee's existing science strategy and to recommendations set forth in its letter reports. In the 1988 letter report, COMPLEX strongly supported SEMPA because it is "in concept uniquely capable of satisfying primary cometary science objectives, in SEMPA's case the detailed chemical, mineralogic, and morphologic characterization of individual cometary dust particles emitted from the nucleus." COMPLEX also noted in its 1987 letter report that "the compositional diversity seen in micron and submicron Halley dust suggests that individual particle measurements from the SEMPA and COMA instruments on CRAF will provide critical data for comparison of cometary matter with chondritic and interstellar grain models." The SEMPA experiment must now be evaluated in the context of how it contributes to the mission's overall goals in competition with other experiments that also analyze the composition of cometary dust.

In the Committee's opinion SEMPA does not address the objective of determining the composition as c6mpletely and as effectively as the CIDEX and COMA experiments do. In addition to supplying information on elemental composition, CIDEX provides information on the composition of volatiles and organics, while COMA provides information on the light elements (hydrogen, lithium, carbon) and on isotopic composition. COMPLEX does not consider the petrologic and mineralogic information provided by SEMPA to have as high a priority as this information on bulk composition. The measurement of composition by X-ray fluorescence in SEMPA is electron-excited, giving lower sensitivity due to

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bremsstrahlung. Thus COMPLEX now recommends deleting SEMPA from the CRAF payload.

The recommendation to delete the MAG, CREWE, and CRIMS experiments is motivated in part by the fact that they address primarily the objective of characterizing the interaction of the comet with the solar wind, which is a lower priority than the study of the comet's nucleus and coma. Furthermore, the design of the baseline CRAF mission largely precludes obtaining data that would substantially characterize the comet's interaction with the solar wind, because CRAF remains very close to the nucleus throughout most of the period of significant activity in the nucleus. COMPLEX places a higher priority on the Suprathermal Plasma Investigation of Cometary Environments (SPICE) than on the other experiments for the study of particles and fields because SPICE, which measures newly injected cometary ions (pickup ions), is a very sensitive monitor of activity in the nucleus, and will also measure the electron densities and velocity distributions that are essential to understanding the chemical processes of the coma. The SPICE instrument, even without MAG, CREWE, and CRIMS, can identify newly injected cometary ions both by their unique velocity distribution and by their composition.

Deletion of the MAGI CREWE, and CRIMS instruments entails a painful loss of scientific return. The MAG would provide knowledge of the solar wind magnetic field during the tail excursion portion of the nominal mission; loss of the MAG would jeopardize the science return from the tail excursion to such an extent that the mission design should be reconsidered. The deletion of CREWE would mean that important plasma physical processes, such as wave generation caused by mass loading, would not be studied. Loss of CRIMS would mean that the mass and velocity distributions of low-energy ions would be less well determined, but these measurements are substantially duplicated by the Neutral Gas and Ion Mass Spectrometer (NGIMS) and SPICE. Overall, the science objectives for the study of particles and fields are judged to be of lower priority than the objectives established for the comet's nucleus and for the coma as stated in the COMPLEX science strategy for primitive bodies.

Based on the numbers presented at our recent meeting by the CRAF project scientist, Dr. Marcia Neugebauer, Table 1 shows the savings that are expected to result from the recommended deletions of SEMPA, MAG, CREWE, and CRIMS plus the repricing and descoping of PENL.

Table 1 Anticipated Savings from Recommended Actions to Reduce CRAF Costs

Action	FY91	FY92	FY93	FY94	FY95	FY91-95
Reprice and Cap PENL	5.5	4.2	0	0	0	9.7
Delete:						
PENL heat shield cover	0	0.4	0.3	0.2	0.1	1.0
SEMPA	4.3	6.8	4.2	2.2	0.9	18.4
CRIMS	0.7	1.1	0.7	0.5	0.3	3.3
MAG	0.5	1.1	0.9	0.6	0.5	3.6
CREWE	1.0	1.8	1.9	0.7	0.6	6.0
MAG/CREWE Boom	0.4	0.8	0.3	0.1	0.1	1.7
Total deletions	6.9	12.0	8.3	4.3	2.5	34.0
TOTAL SAVINGS	12.4	16.2	8.3	4.3	2.5	43.7

NOTE: Numbers from Appendix B

Appendix C indicates that NASA anticipates a budgetary shortfall of approximately $12M in FY91 and $20M in FY92. COMPLEX notes that its recommendation solves the FY91 shortfall completely and allows some carryover to FY92. The savings, plus the carryover, do still leave a shortfall of $3.4M in FY92. *COMPLEX further recommends that NASA overcome the small FY92 shortfall through a combination of less drastic measures, including shifting of some costs into later years.* Although a $32M cost reduction appears to be necessary, the Committee's recommendation would actually result in a total development runout savings of $43.7M. Therefore, COMPLEX is confident that its recommendation is satisfactory for solving the budgetary problem.

The Committee also notes that if the selection of experiments for the Cassini mission does not include the Visual and Infrared Mapping Spectrometer (VIMS) experiment, this will place an additional burden on CRAF of approximately $7M. *If the VIMS is not selected for the Cassini mission, COMPLEX recommends removing VIMS from CRAF, and restoring SEMPA.*

Deletion of the penetrator would severely compromise the ability of the CRAF mission to address the highest-priority goals identified by COMPLEX. For this reason, COMPLEX recommends against Option 1 (the deletion of PENL) as presented by the CRAF PSG. The Committee noted in its 1988 letter report "the unique ability of the penetrator instruments to address in situ the highest priority science objective ... namely, determination of the dust and volatile composition, state, and physical properties of the [comet] nucleus."

With regard to characterizing bulk elemental composition within the comet nucleus, the penetrator's Gamma-Ray Spectrometer (GRS) will make elemental in situ measurements of approximately one metric ton of the material in which the penetrator is embedded. The sensitivity of the GRS appears to be adequate to assess the degree of chemical fractionation (e.g., distinguishing refractory from volatile elements, iron from silicon) to allow comparison with known types of primitive meteorites.

With regard to ices, the penetrator's Differential Scanning Calorimeter and Evolved Gas Analyzer (DSC/EGA) combination is the only experiment capable of determining the phase structure of the icy component of the comet's nucleus and how the volatile molecules are trapped in the ices. It is crucial to understand the mechanism for trapping volatiles in cometary nuclei because such trapping processes provide constraints on the conditions leading to the formation of comets. While other instruments measure the abundances of parent molecular species in the coma, these measurements are ambiguous with respect to the abundances of these species in the environment of cometary formation. The DSC/EGA experiment provides the means to resolve such ambiguities by measuring the ice structure and trapped gases. In its 1987 letter report, COMPLEX recognized that the data obtained in the DSC/EGA analysis "does not ... appear accessible by any other means."

The Committee notes that a repricing of PENL to yield the savings shown in Table 1 has been proposed by the principal investigator, but not confirmed by NASA. If such a repricing is, in fact, not entirely feasible, the cap on the penetrator cost will require a descoping of the penetrator. COMPLEX finds that the accelerometers and thermal probes have the lowest scientific priority of the penetrator experiments. The Committee received no information concerning either the management or technical risk of the penetrator, but the principal investigator's statement that it is not inherently more risky than several of the other experiments was not contested by the JPL or NASA representatives at the COMPLEX review.

As indicated above, Option 2 proposed by the CRAF PSG involves a mandatory list of descoping options (Table A in Appendix A) and an optional list of possible deletions (Table B in Appendix A), only some of which need to be selected. COMPLEX recommends against Option 2 altogether because the Table A deletions taken in total would significantly and unnecessarily increase the technological risk in developing many of the science instruments, and would jeopardize scientific preparation that is necessary for the mission. In particular, the following actions listed in Table A would result in significant loss of scientific return and/or unnecessary technological risk: deletion of the Thermal Infrared Radiometer Experiment's (TIREX) engineering unit; delay of gas/dust modeling; deletion of the SPICE electron measurements; deletion of JPL's calibration target for TIREX, VIMS, and the Imaging Science System (ISS); deletion of the X-Ray Fluorescence (XRF) function from the Cometary Ice and Dust Experiment (CIDEX); and general descoping of prelaunch science activities.

COMPLEX expresses its dismay that such a major reduction in mission scope has had to be undertaken so early in an approved mission. The Committee strongly believes that the fully configured CRAF mission is responsive to the goals and strategies articulated in previous reports and that the deselection of instruments is not conducive to excellence in planetary scientific exploration. Although the proposed descoped CRAF would also remain responsive to these science goals, COMPLEX notes that any further reduction of mission scope may irreparably impair CRAF's ability to respond adequately to the Committee's stated science goals and objectives.

- **Appendix A**
- **Appendix B**
- **Appendix C**

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Appendix A

Options Proposed by NASA to Reduce the CRAF Mission's Budgetary Shortfall

OPTION 1. Delete the penetrator

Item	$k:	FY91	FY92	FY93	FY94	FY95	FY91-95
Instrument - Hardware & science		11299	21560	14521	10975	4596	62951
Penetrator mission design		128	137	142	77	80	564
Thermal shield & cover		0	800	600	400	200	2000
Science Coordinator		24	37	40	41	45	187
JPL Engineering oversight		126	162	170	180	152	790
TOTALS		11577	22696	15473	11673	5073	66492

NOTE: The information in Appendices A and B was provided to the Committee in a presentation by Dr. Marcia Neugebauer, the CRAF Project Scientist, on 12 July 1990.

OPTION 2. Delete the items listed in Table A and then pick enough items from Table B to make up the necessary totals.

Table A

Item $k:	FY91	FY92	FY93	FY94	FY95	FY91-95
Delete TIREX Engineering unit	11	198	121	0	0	330
Delay development of SEMPA software	0	60	170	0	0	230
Delete redundancy of SPICE/CRIMS electronics	84	194	56	33	0	367
Delete Penetrator heat shield cover	0	400	300	200	100	1000
Reduce prelaunch MIPS support to ISS	20	25	105	150	200	500
Delay gas/dust modeling to post-launch	60	145	154	98	77	534
Delay spare VHM sensor for MAG (Note 1)	156	154	20	-221	-109	0
Delete electron measurements from SPICE	525	394	349	163	0	1431
Delete position/direction meas. from CODEM	22	297	300	22	0	642
Delete SIMS mode from NGIMS	223	317	113	51	22	726
Delete JPL Calib system, add target to TIREX	309	600	1025	247	59	2240
Delete XRF from CIDEX	375	1045	635	180	65	2300
Reprice and cap the Penetrator costs (Note 2)	5500	4200	0	0	0	9700
Descope pre-launch science activities (Note 3)	550	834	932	1053	1065	4433
TOTALS	7835	8864	4280	1976	1479	24433
Shortfall of target	4165	11136				

Table B

Item $k:	FY91	FY92	FY93	FY94	FY95	FY91-95
Delete rest of CIDEX, restore SIMS to NGIMS	1562	4511	2924	962	517	10476
Delete CREWE	1078	1824	1922	736	512	6072
Delete CRIMS	713	1203	763	624	431	3734
Delete IDSs (prelaunch only)	72	87	102	109	80	450
Delete ISS wide angle camera	370	675	580	15	0	1640
Delete MAG	384	978	851	845	569	3627
Delete MAG/CREWE boom	391	785	333	122	60	1690
Delete PENL accelerometers	264	585	209	281	12	1351
Delete PENL EGA	765	2125	666	1046	22	4623
Delete PENL EGA/DSC	1251	2889	1108	1648	125	7022
Delete PENL GRS	835	1330	757	1168	75	4165
Delete PENL thermal probes	530	806	355	522	13	2226
Delete SEMPA	4298	6681	4007	2203	890	18079
Delete rest of SPICE (incl CRIMS electronics)	1235	2561	1894	361	377	6428
Delete rest of SPICE (add electronics to CRIMS)	1187	2416	1723	307	363	5996
Delete TIREX	2079	4254	2781	842	251	10217
Delete VIMS (Note 4)	4366	7117	4069	1367	1799	18718

There was no consensus about which Table B deletion(s) should be selected. Criteria to be considered are:

- Priority of science (1. Nucleus, 2. Coma, 3. Solar-wind interaction)
- Quality of the measurement
- Risk—both technical and financial
- Balance

Note 1.

There are possibly larger savings to the magnetometer if the European (British and German) Co-Investigators can be persuaded to pick up more of the hardware responsibility:

Item $k:	FY91	FY92	FY93	FY94	FY95	FY91-95
Europeans responsible for S/C interfaces	206	204	366	117	0	918
Delete VHM sensor; hardware all European	226	546	431	232	40	1476

These two options cannot be added together, nor can they be added to the option given in Table A.

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Note 2

The Penetrator PI believes he can cut the cost of his investigation by $5.5M in FY91 and $4.5M in FY92 without descoping the science return. He has also agreed to descope as necessary to stay within budget. If these cost reductions in FY91 and 92 cannot be realized, there will have to be deepter cuts selected from Table B.

Note 3. Each investigator estimated the amount by which his team's prelaunch science budget could be descoped as follows:

Investigation	Plan	% cut	$k cut	Impact or rationale
CIDEX	694	12	85	Limit analysis of analog materials to last 2 years, 20% cut in effect Decrease from 1 to 2 team meetings/yr in 91-94 Drop support for in-house Co-I science activities
CODEM	114	80	91	TBD
COMA	1067	40	427	TBD
CREWE	1040	50	520	Limit duplicate Co-I travel to PSG meetings, etc. Cut Co-I science funds to minimum level
CRIMS	492	30	148	Delay reduction (but not inspection) of calibration data Reduce coma modeling to minimum required by Project Exploit commonality with ISTP onboard data processing
ISS	2347	20	469	Delay software development not essential to calibration
MAG	725	19	138	Reduce number of team meetings and travel; more faxing & phoning
NGIMS	335	0	0	n/a
PENL	1768	20	354	Eliminate support for 3 Co-Is; delay nucleus modeling to post-launch Cut another Co-I by 50%, delay accelerometer interpretation studies Cut out one team meeting per year; increased phone calls.
SEMPA	760	15	114	Reduce Co-I PSG attendance. Delay Co-I involvement in developing instrument operation scenarios
SPICE	1603	40	641	Electron measurements assumed deleted Postpone development of analysis and display software
TIREX	168	0	0	n/a
VIMS	3941	25	985	TBD
IDSs	922	50	50	Delay model development and special studies
TOTALS	15976		4433	

Note 4

The VIMS costs = (C/C hardware costs, including dedicated contingency)/2 + 0.75 (CRAF VIMS science team costs) + Science coordinator cost.

The factor 0.75 accounts for the 25% reduction of VIMS science costs deleted in Table A.

If CRAF VIMS were dropped, the runout cost of the Cassini VIMS would increase by $7254k.

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Appendix B

Current CRAF Investigation Costs in Real Year K$

	FY90	FY91	FY92	FY93	FY94	FY95	TOTAL	% INCR
CRIMS	183	671	1133	689	548	348	3572	14
SEMPA	587	4309	6783	4221	2250	939	19089	20
CIDEX	431	2101	5788	3583	1100	504	13507	49
MAG	292	529	1118	856	618	458	3871	36
SPICE	285	1906	3184	2333	596	354	8658	4
PENL	1292	11299	21560	14521	10975	4596	64243	143
MSN DSN	1	128	137	142	77	80	565	N/A
THRMSHLD	0	0	400	300	200	100	1000	N/A
NGIMS	258	2118	3184	1942	927	500	8929	24
CREWE	219	1039	1818	1935	738	568	6317	23
CODEM	244	906	1244	1633	589	445	5060	-4
TIREX	214	2024	4052	2797	732	137	9956	91
COMA	87	150	224	243	257	193	1154	88
VIMS HDW	458	3511	5301	2944	1446	697	14357	-8
VIMS SCI TM	117	401	572	799	1061	1128	4078	N/A
ISS HDW	2108	6688	9872	8042	4507	776	31993	66
ISS SCI/MIPS	128	288	493	728	904	1312	3853	N/A
SCAS	8	305	901	1027	247	60	2548	N/A

NOTE: Basis for % increase is proposed Tempel 2 hardware and science costs shifted in time and inflated for the Kopff mission (6/86 baseline) and then inflated to current year dollars (FY86-FY90).

VIMS hardware costs shown exclude committed reserves as follows (includes Cassini VIMS reserve)

FY91	FY92	FY93	FY94	FY95	FY96
972	2520	789	290	139	31

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Appendix C

CRAF/CASSINI SCIENCE COST PHASING ISSUE (REAL YEAR MILLION DOLLARS)

(REAL YEAR MILLION DOLLARS)

	FY 91	FY 92
CRAF SCIENCE REQUIREMENT	44.0	79.0
CASSINI SCIENCE REQUIREMENT	24.8	53.1
TOTAL	68.8	132.1
AVAILABLE TO PROJECT FOR C/C SCIENCE	38.4	82.2
ANNUAL SHORTFALL	30.4	49.9 ~~85.9~~
ALLOCATIONS FOR SCIENCE		
CASSINI	12.4	27.7
CRAF	26.0	54.5
CRAF SHORTFALL	18.0	24.5
OFFSETS	(6.0)	(4.5)
CRAF RESIDUAL PROBLEM	12.0	20.0

NOTE: This information was provided to the Committee in a presentation by Dr. Howard Wright, the CRAF/Cassini Program Manager, on 12 July 1990.