United States Department of the Interior

GEOLOGICAL SURVEY
WASHINGTON, D.C. 20242

Physics Building, Mail Stop 990

October 7, 1980

Mr. Joseph M. Brown, Jr.
License Management Branch
Division of Fuel Cycle and Material Safety
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mr. Brown:

This letter is a request for amendment of Materials License 45-15923-01 to increase License item 6Q (any byproduct material) for item 7Q (activated samples) from 500 millicuries total to 530 millicuries total. The additional authorization of 30 millicuries of activated samples is sought for use by Dr. John F. Sutter for radioactive dating research by potassium-argon methods. Dr. Sutter's extensive experience in this research, the procedure to be used, and a discussion of radiation hazards incident to the normal procedure and to accident conditions are detailed in the attachments.

We hope to be in a position to commence the research in late November and should appreciate amendment of the license by that time. Should any questions arise, please call me at 703-860-7662 (FTS 928-7662) or Dr. Sutter at 703-860-6591 (FTS 928-6591).

Very truly yours,

Allan B. Tanner

Allan B. Tanner
Radiation Protection Officer

Enclosures

On-The-Job-Training Relevant to Above:

Employer	Type of Work	Time Applicable To (a)	(b)	(c)	(d)
Rice Univ. 1965 ↓ 1969	Operation of:				
	alpha counter	✓	✓	✓	
	gamma-ray spectrometer	✓	✓	✓	
	x-ray flourescence spectrometer	✓	✓	✓	
	x-ray diffractometer	✓	✓	✓	
	mass-spectrometer	✓	✓	✓	
NASA, Johnson Space Center 1969-1970	Chemical separations using radioactive tracer	✓	✓	✓	
State University of New York at Stony Brook (SUNYSB) 1970-1971	Neutron irradiation of various materials, including rock and mineral samples, at the High-FLUX Beam reactor at Brookhaven National Lab and Mass spectrometric analysis of rare gases samples from irradiated at SUNYSB.	✓	✓	✓	
	Taught seminar in geochemistry	✓	✓	✓	

(continued on page 3)

Experience with Radiation:

Isotope	Maximum Amount	Where Experience Was Gained	Duration	Type of Use
^{32}P, ^{33}P, ^{35}S, ^{45}Ca, $^{49}Ca/^{49}Sc$, ^{51}Cr, ^{55}Fe	100 mCi	State University of NY at Stony Brook (Dept. of Earth and Space Sciences)/High Flux Beam Reactor, Brookhaven National Lab, Brookhaven, NY	Oct 70 - Oct 71	Mass spectrometric analysis of rare gases produced by neutron irradiation of rock & mineral samples.
^{54}Mn, ^{59}Fe, ^{86}Rb, ^{46}Sc, ^{47}Sc, ^{58}Co, ^{60}Co		Dept. of Geology and Mineralogy, Ohio State Univ./ Geological Survey TRIGA Reactor, Denver, Colorado and Phoenix Memorial Lab., Univ. of Michigan, Ann Arbor, Mich.	Oct 71 - Sept. 80	Mass spectrometric analysis of rare gases produced by neutron irradiation of rock & mineral samples.

Name: JOHN F. SUTTER Title: GEOLOGIST

Formal Education:

Institution and Location (City & State)	Dates of Attendance	Degree	Field
Capital University Columbus, Ohio	1961-1965	B.S.	Geology
Rice University Houston, Texas	1965-1968	M.A.	Geology
Rice University Houston, Texas	1968-1970	PHD	Geology

Formal Courses Relevant To:
(a) Principles and practices of radiation protection.
(b) Radioactivity measurement standardization and monitoring techniques and instruments.
(c) Math calculations basic to use and measurement of radioactivity.
(d) Biological effects of radiation.

Course	Where?	How Long?	Relevant to (Check) (a)	(b)	(c)	(d)
Math	Capital U.	1½ yr.			✓	
Chem	Capital U.	3 yr.	✓	✓		
Biology	Capital U.	1 yr.				✓
Physics	Capital U.	1 yr.	✓	✓	✓	
Geochemistry	Rice U.	1 yr.	✓	✓	✓	✓
Radiogeology	Rice U.	½ yr.	✓	✓	✓	✓
Thermodynamics	Rice U.	½ yr.			✓	
Seminar in Nuclear Geochemistry	Rice U.	½ yr.	✓	✓	✓	✓

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Description of Proposed Experiment:

Granular rock and mineral samples will be encapsulated in pure aluminum foil and then encapsulated in high-purity quartz vials which are sealed in air. The quartz vials will be placed inside a high-purity aluminum or quartz reactor vessel and lowered into the core facility of a nuclear reactor. The reactor vessel, containing the sample vials, will be irradiated with a fast neutron dose of about 2×10^{18}. After irradiation, the reactor vessel will be stored in the pool of the reactor for 14-21 days to allow for decay of short-lived radionuclides. After the appropriate cooling period, the reactor vessel will be placed in a DOT-type 7A container and transported to the Reston National Center and taken to Rm 3D-237 (Neutron Activation Storage Facility) for storage.

Individual quartz vials, containing the aluminum foil-encapsulated rock and mineral grains, will be transported from storage to Room 3B-425 in a lead pig. Once in 3B-425 a quartz vial will be placed in a glove box, broken open, and aluminum foil capsules removed from the vial. One AL capsule will be opened and the contents poured into a high-purity molybdenum crucible, and the other AL capsules placed in a glass vial and returned to 3D-237 for storage.

The molybdenum crucible, containing the rock or mineral grains, will then be lowered into a vessel made of pyrex and quartz. The vessel will then be transported to Rm 3B-429 in an unbreakable, sealed container and attached to an ultra-high vacuum system. The rock and mineral grains will release less than 5×10^{-14} moles of argon during pumping to ultra-high vacuum. Under static vacuum conditions, an induction heating coil will be placed around the pyrex and quartz vessel containing the molydenum crucible which in turn holds the irradiated rock or mineral grains. The molybdenum crucible will then be induction heated to a sufficient temperature to melt the rock or mineral grains ($\sim$1,000-1,600°C). Gases contained in the

On-The-Job-Training Relevant to Above:

Employer	Type of Work	Time Applicable To (a)	(b)	(c)	(d)
Ohio State University (OSU)	Neutron irradiation of rock and mineral samples at the TRIGA reactor, Denver Fed. Center, Denver, Colorado and at the reactor of the Phoenix Memorial Laboratory, Univ. of Michigan, Ann Arbor, Mich.	✓	✓	✓	
1971 ↓ 1980	Mass spectrometric analysis of irradiated rock and mineral samples at OSU.	✓	✓	✓	
	Taught course in Isotope Geology 4 times.	✓	✓	✓	✓
	Taught seminar in geochemistry	✓	✓	✓	✓
	Supervised 10 student thesis projects involving the use of radioactive materials.	✓	✓	✓	✓
	Director of the K/Ar, $^{40}Ar/^{39}Ar$, and Fission Track Dating Laboratories at OSU.	✓	✓	✓	✓

Safety Analysis

About 5-5.5 mCi of activity, in the form of irradiated granules of rock or mineral samples, will be transported from the nuclear reactor to Rm 3D-237 (Neutron Activation Storage Facility) of the Reston National Center in a DOT-type 7A container. This container will also be used as a storage facility in Rm 3D-237. Appropriate labelling of all transporting containers will be accomplished at the reactor, and transport of the DOT Type 7A container will follow all guidelines for interstate transport of radioactive materials.

In Rm 3D-237 an individual quartz vial containing a maximum of 0.7mCi of activity will be removed from the storage container by means of a forceps and placed in a Pb pig.** The pig will be hand carried from Rm 3D-237 to Rm 3B-425 along the route shown in Figure 1. A survey instrument* will be available in both 3D-237 and 3B-425. Once in 3B-425, the quartz vial will be removed from the Pb pig, using forceps, and placed in a glove box located on a table as shown in Figure 2. The quartz vial will be broken open inside the enclosed box by means of a small hammer or pliers and the aluminum vials removed with forceps. All but one of the aluminum vials will be placed in a glass vial and returned to the Pb pig and returned to Rm 3D-237 for storage. The one remaining aluminum vial will be broken open and emptied into a molybdenum crucible. This crucible will then be lowered into a pyrex and quartz vessel. The vessel will then be hand carried next door to Rm 3B-429 and attached to an ultra-high vacuum line as shown in Figure 3. At this point, solid radioactive waste in the form of the broken quartz vial and the empty aluminum capsule are present inside the glove box in 3B-425,as well as contaminated hammer, pliers, and forceps. The waste will be quantitatively wrapped in multi layers of paper tissues (kimwipes) and taped to insure no fragments of broken quartz or aluminum can escape and the tools will be wiped with tissues dampened with ethanol and the tissues added to the waste. This small package of waste will then be stored

* Ludlum Measurements Model 3 meter with Model 44-6 thin-wall GM tube (30 mg/cm^2), calibrated annually by the Radiation Protection Officer. Ranges are 0-500. 0-5k, 0-50k, and 0-500k c/m.

** Conventional custom cyclindrical shield with minimum 5-cm Pb wall thickness.

rock or mineral grains will be driven off on melting and the gas mixture reacted with various gettering devices to remove all components except the inert (rare) gases. The inert gases will then be let in to the ionization source of a mass spectrometer operated in a static vacuum mode. The inert gases will be ionized and collimated into a beam and mass analyzed, and after analysis the inert gases will be pumped into the body of a triode ion pump especially built for pumping inert gases.

To prepare for the next experiment, the vessel of pyrex and quartz will be removed from the ultra-high vacuum system, transported in an unbreakable, sealed container to the glove box in Rm 3B-425 and the molybdenum crucible containing the melted radioactive mineral or rock sample (now a glass at room temperature) removed and placed in a can for solid radioactive waste. The pyrex and quartz vessel will be placed in a fume hood in Rm 3B-425 and filled with nitric acid for cleaning in preparation for reuse. The nitric acid and wash water will be transferred to a storage container and the cleaned pyrex and quartz vessel will be placed in a drying oven in Rm 3B-425.

After all of the aluminum foil capsules from a quartz vial are handled in a similar manner to that described above, and after all quartz vials have been opened and the samples analyzed, a cycle is complete. More rock and mineral grains are prepared for irradiation to start the next cycle. A maximum of 5-10 cycles per calendar year is anticipated.

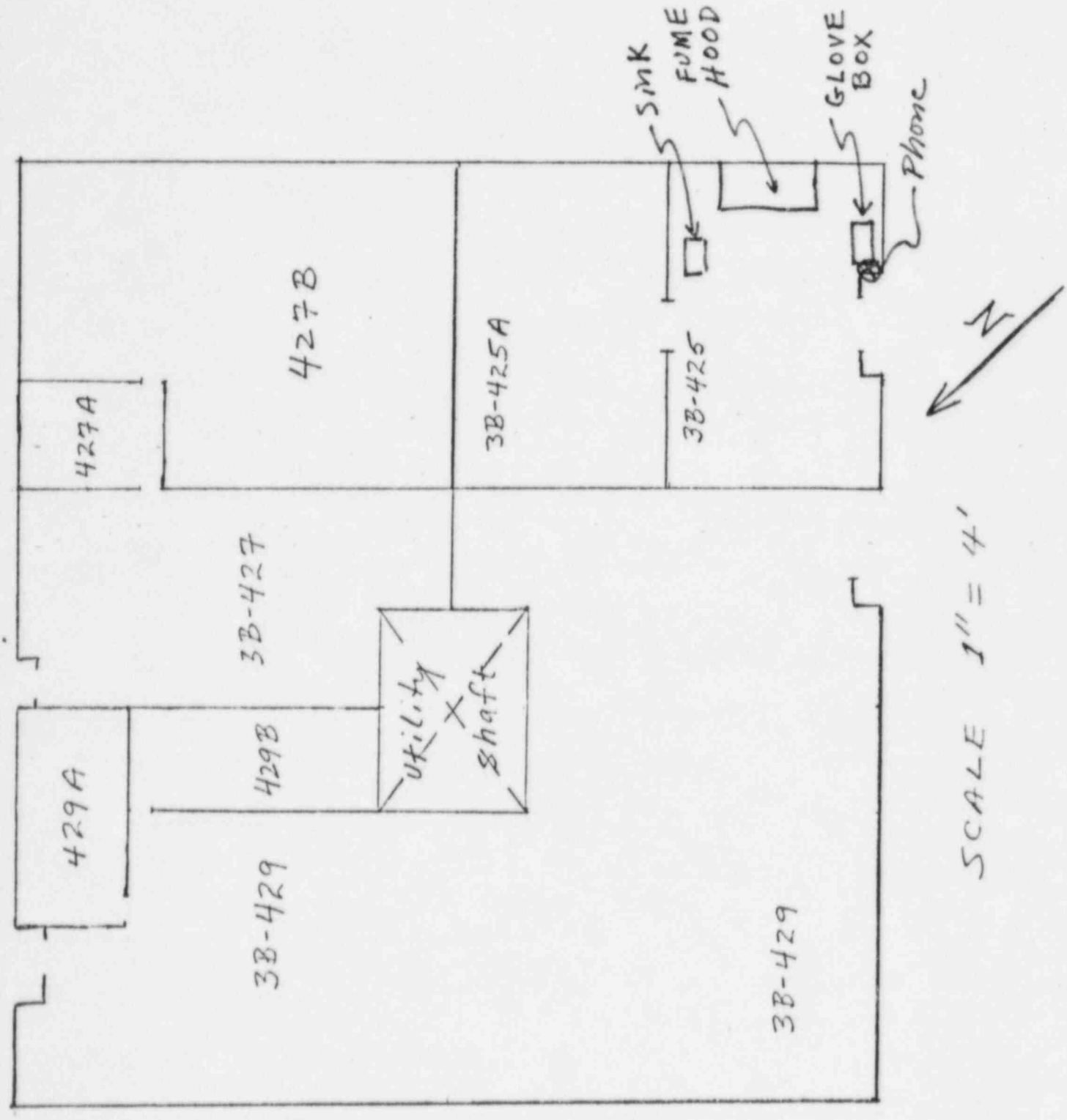

Figure 2
Plan showing location of facilities for loading of vacuum vessel.

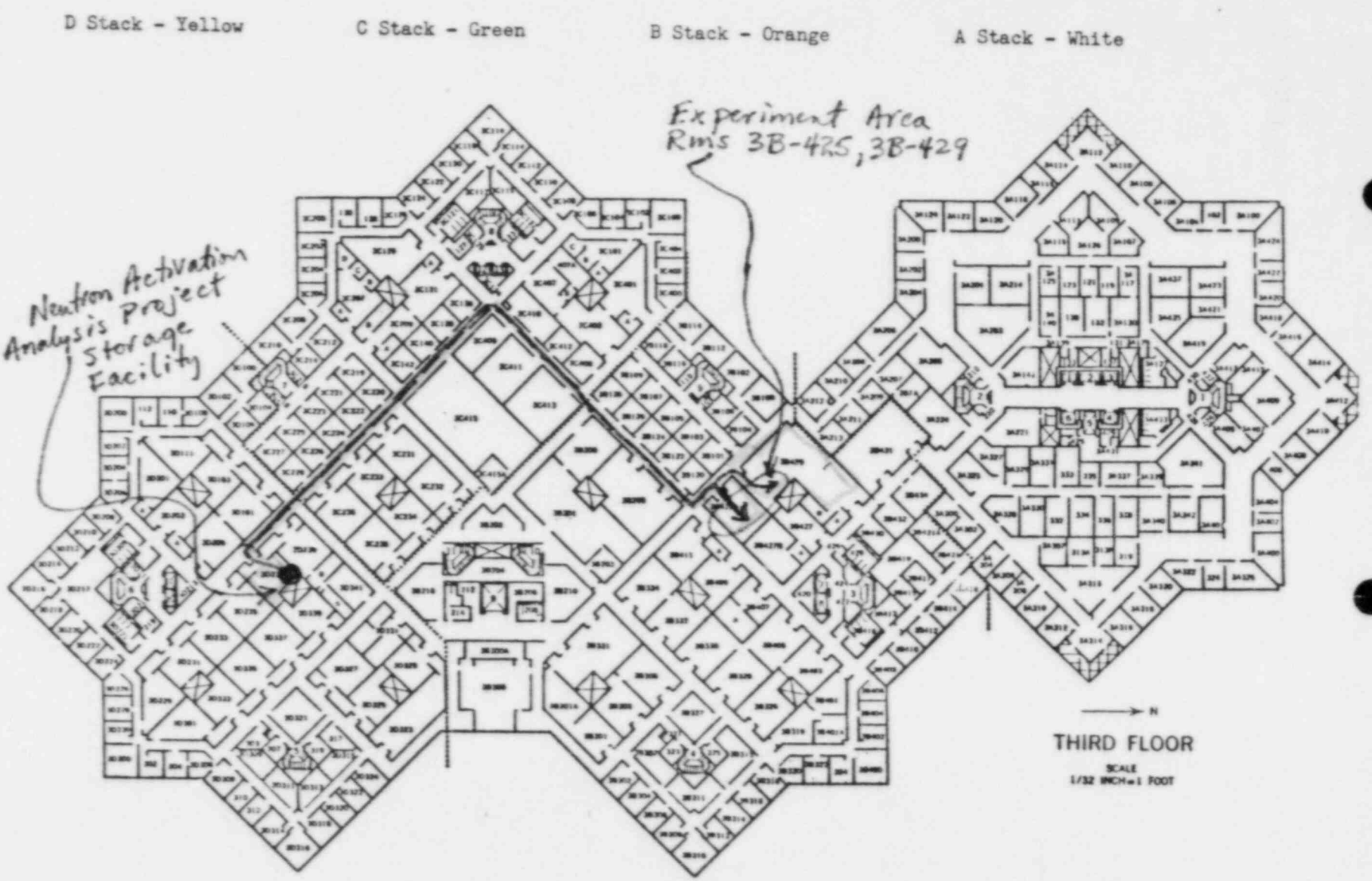

Figure 1
Plan of Third Floor, showing rooms used for storage and experiments

in the proper solid radioactive waste can and the glove box and tools will be surveyed with a total β,γ meter to see that no activity above background can be detected.

Both Room 3B-425 and 3B-429 will be locked when not occupied. Since the bulk of the activity is associated with the granular rock samples, now in the pyrex and quartz vessel in Rm 3B-429, I propose that all persons working on a daily basis in Rms 3B-429 and 3B-425 should, at least initially, be put on a film badge program. These people are: Tom Stern, Joe Arth, John Sutter, Marcia Newell, and Ted Denton. As other personnel begin to work in these areas (as permanent or part-time employees), they should be added to the film badge program if it seems appropriate or they desire it. My previous ten years of experience indicates that no one, except those actually handling the radioactive materials, will receive doses exceeding 100 millirem per calendar quarter. However, to insure this, appropriate shielding of the area in 3B-429 containing the activity will be emplaced. Initially only John F. Sutter will handle the radioactive materials and will be responsible for shielding the work areas from other personnel. The fact that Rms. 3B-425 and 3B-429 have limited access, control is relatively easy.

During the experimental procedure in Rm 3B-429 involving the radioactive samples, a couple of situations could evolve that would lead to limited contamination of the general work area:

1. The radioactive sample is encased in a pyrex and quartz vessel. This vessel could break and the radioactive sample with a total activity of up to 0.7 mCi could fall to the floor in the area of the vacuum line. This has happened twice in my past ten years of experience. Each time the cleanup (decontamination) procedure has been accomplished in a matter of a couple of hours by simply sweeping the radioactive granules of rock and/or minerals into a dustpan and then a damp wipe of the area followed by a general survey using a total β,γ meter and subsequent

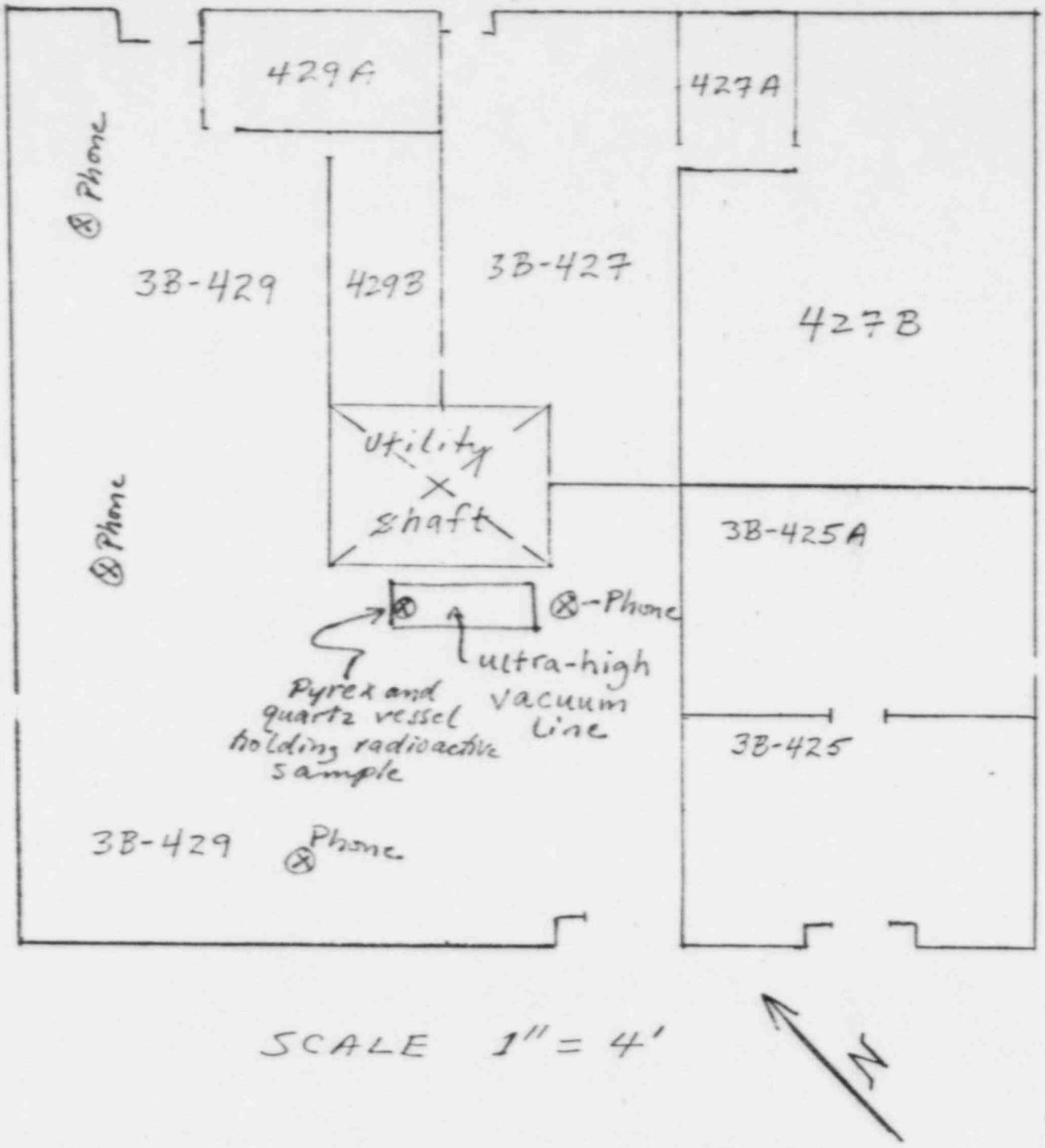

Figure 3
Plan showing location of high-vacuum apparatus.

No radioactive gaseous molecules are produced in this procedure so no special hood exhaust or filters are needed. However the nitric acid is now radioactive because of the fact that metallic ions, some of which are radioactive, are dissolved in it. The nitric acid and the subsequent wash water will be transferred to a storate container and reused for several experiments. It will then be neutralized (pH of 7-8), evaporated to a minimum practical volume and disposed of using procedures outlined for acqueous radioactive waste. Regular surveys of the fume hood area and tools used for this purpose will be done to ensure no contamination of work surfaces. The cleaned py ex and quartz vessel will then be placed in a drying oven in 3B-425 for storage till reuse. When this pyrex and quartz vessel breaks or becomes unusable, it will be placed in solid radioactive waste disposal to ensure no residual activity, that might be present, be put into the natural environment. Radioactive waste will be disposed of with that from the Neutron Activation Analysis Project by contract with the U.S. Army, Rock Island, Illinois.

wipe tests. Clean-up of this type of spill is facilitated by the fact that the radioactive material is in the form of insoluble granules rather than a powder.

2. The vacuum line is made of glass and is breakable. Also during the experiment, radioactive samples are melted and gases evolved and purified in this glass vacuum line. ^{37}Ar and ^{39}Ar, both radioactive, are present in the purified gas mixture. If the glass vacuum line were broken during the experimental procedure, this ^{37}Ar and ^{39}Ar could be liberated into the air of the general work area, Rm 3B-429. The maximum amount of ^{37}Ar in any one experiment is $1x10^{-11}$ moles. These quantities represent an activity of 375 μCi of ^{37}Ar and 0.0266 μCi of ^{39}Ar. The volume of Rm 3B-429 is $>4x10^{8}$mL so the activities of ^{37}Ar and ^{39}Ar would be $<9.4x10^{-7}$ μCi/mL and $<6.65x10^{-11}$ μCi/mL respectively if the argon from an entire experiment were vented into the room in a static condition. Since the air in Rm 3B-429 is recycled every 4-5 minutes, no possibility of a hazardous level of radioactive argon should be encountered in this experiment.

After the experimental procedure is complete, part of the activity is in the form of a gaseous mixture and part is solid. The gases will be pumped into, and physically trapped in, the body of a triode ion pump and involves no potential problem. The solid material that remains is a bit more difficult to deal with. Most of it is now in the form of a glass in the bottom of a molybdenum crucible, but some is in the form of a metallic film coating the inside of the pyrex and quartz vessel attached to the vacuum line. The molybdenum crucible and the glassy residue contained therein is removed from the pyrex and quartz vessel inside the glove box in 3B-425 and disposed of as solid radioactive waste. Since the pyrex and quartz vessels need to be reused, and since they need to have the radioactive, metallic film removed to be reusable, they are filled with nitric acid to dissolve this film. This cleaning procedure will be done in a fume hood located in Rm 3B-425 (Figure 2).

ORGANIZATION: U.S. Geological Survey

ADDRESS: Reston National Center, MS 981

NAME: JOHN F. SUTTER TELE: 860-6591

EXPERIMENTAL PROPOSAL #

DATE RECEIVED:

1. SAMPLE MATERIAL: Rocks and Minerals

2. ELEMENT(S) TO BE DETERMINED: ~~Ca~~ Argon

3. ORGANIC CONSTITUENTS: % 0

4. INORGANIC CONSTITUENTS: % 100

5. NATURE OF SAMPLE: (See attached sheet)

☐ SOLID ☐ LIQUID ☐ GAS ☐ POWDER ☒ OTHER (Specify) Granules

6. WEIGHT OF EACH SAMPLE: 2 grams

7. NUMBER OF SAMPLES: 8

8. TOTAL WEIGHT PER IRRADIATION: 16 grams

9. ENCAPSULATION:

☐ I ☒ II ☐ IIS ☐ III ☐ IIIS

10. DESCRIBE ENCAPSULATION SPECIFICALLY: See attached sheets %VOID 40

11. IRRADIATION LOCATION: G-2 (LOWER CORE)

12. MAXIMUM EXPOSURE TIME: 10 Hours

13. ESTIMATED ACTIVITIES OF PRINCIPAL NUCLIDES IN MILLICURIES PER IRRADIATION:

NUCLIDE	^{24}Na	^{31}Si	^{56}Mn	^{59}Fe	^{45}Ca	^{60}Co	^{46}Sc	^{51}Cr	^{28}Al	attached sheets
ACTIVITY	400,000	8,000	18,000	1.44	1.90	0.13	2.06	1.07		attached

14. EXPECTED MAXIMUM SAMPLE TEMPERATURE: < 102 °C

REFERENCE: NBS Tech. Note 548 Section 3B

15. EXPECTED PRESSURE INCREASE (IN ATMOSPHERES):

160°F 0 200°F 0 240°F 0

REFERENCE: NBS Tech. Note 548 Section 3B

16. EXPECTED CHEMICAL RELEASE: None

REFERENCE: Irradiation of samples for $^{40}Ar/^{39}Ar$ Dating at USGS, The Geological Survey TRIGA reactor (GSTR) D. Trimble, Alexander Langhorne, Kraker (1980)

17. NUCLEAR REACTIVITY: None

REFERENCE:

18. BRIEF DESCRIPTION OF EXPERIMENT AND/OR ADDITIONAL INFORMATION FROM ABOVE QUESTIONS:

See attached description;

HAZARDS EVALUATION COMMITTEE/HEC SUBCOMMITTEE RECOMMENDS PROPOSAL BE APPROVED SUBJECT TO THE FOLLOWING CONDITIONS:

FROM: DATE

CHAIRMAN, HAZARDS EVALUATION COMMITTEE/HEC SUBCOMMITTEE

APPROVED: DATE

CHIEF, REACTOR RADIATION DIVISION

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

September 26, 1980

Nate Bickford
National Bureau of Standards
Bldg. 235, Rm A-106
Washington, D.C. 20234

Dear Nate:

Enclosed is a copy of my experiment proposal for circulation at NBSR. I've tried to keep it short and to the point, so please let me know if any additional information is needed. I do have experiment authorizations for the very experiment I am proposing at both the TRIGA reactor at the U. S. Geological Survey in Denver and at the reactor in the Phoenix Memorial Lab at the University of Michigan. Also I have done this type of experiment at the High Flux Beam reactor at Brookhaven. All in all I have been doing this type of experiment since 1971, as have many other researchers.

Briefly, the purpose of the experiment is to measure ages of rocks and minerals by using the ^{40}K---^{40}Ar natural decay scheme. In the experiment, a portion of the ^{39}K in the rock or mineral is converted to ^{39}Ar via the n,p reaction in the core of a nuclear reactor. Because the ratio of $^{39}K/^{40}K$ is a constant for all natural materials, ^{39}Ar can be used as a measure of ^{40}K if minerals of known ^{40}K content (stds) are irradiated along with the unknowns. Also since ^{39}Ar has a $t_{\frac{1}{2}}$ of about 265 years, it can be regarded as a stable isotope of argon in terms of the time needed for analysis. So then after the rocks and minerals are irradiated to produce ^{39}Ar, they are melted in an ultra-high vacuum line, the argon liberated, and then the isotopic composition of the argon measured using a gas source mass spectrometer. It should be pointed out that no minerals used in this method of isotopic dating lose argon at temperatures below about 250°C so temperatures produced in the samples during irradiation will not produce argon diffusion from the samples.

As I mention in this proposal, rotation of the irradiation package is essential to ensure no circumferential flux gradients, but except for that aspect, no special handling is required.

Thank you for considering this application.

Sincerely,

John F. Sutter

Dr. John F. Sutter
Isotope Geology

has elapsed, the entire irradiation package (Aluminum reactor can and quartz vials containing samples) will be transported from NBSR to USGS, Reston National Center in a DOT Type 7A container. Five to ten irradiations of this type per year is anticipated at present.

Addendum to Experiment Proposal

5. Nature of Sample:

Sample will consist of rock and/or mineral grains whose size will range from 0.1 - 1.0 mm diameter. No powdered material will be present.

6) Weight of each sample:

Weight quoted does not include encapsulation.

10. Description of encapsulation:

Rock and mineral grains will be first encapsulated in pure aluminum vials. These vials will be sealed by crimping the ends. The aluminum vials will then be encapsulated in high-purity quartz vials sealed by glassblowing in air. Approximately 40% of the volume of the quartz vial will be void space.

18. Experiment Description:

Approximately 16 grams of granular rock and/or mineral samples will be encapsulated in aluminum vials which in turn will be encapsulated in quartz vials. The quartz vials (6 mm I.D. x 8mm O.D. and approximately 12.5 cm long) will be placed in an aluminum reactor vessel for use in the G-2 facility at NBSR. This package will be transported to NBSR and lowered into the mid portion of the lower core. Maximum irradiation time is anticipated to be 10 hours depending on the rate of production of ^{39}Ar from ^{39}K via the n, p reaction. Since horizontal (radial) flux gradients cannot be measured precisely and accounted for in my experiment, I propose that the irradiation vessel be rotated during irradiation to insure a uniform flux distribution.

After irradiation, a cooling period in the reactor pool of 14-21 days is anticipated to allow short-lived radionuclides to decay away. When sufficient time

Predicted Activities in MCi

for Irradiation of Rock and Mineral Grains

in the G-2 Facility of NBSR

Assume:

1) All weights of materials to be irradiated is a maximum (127.3 grams)
2) Flux is maximum (1.2×10^{14} n/cm^2/sec)
3) Duration of irradiation is maximum (10 hours)
4) Assume Chemistry of all rock and/or mineral samples is such that the production of long-lived radionuclides is maximized.

Element	wt Max (grams)	Predicted activity (mCi)[1] t_0	t_{14} d	t_{21} d
Irradiation Vessel:				
AL	18.1	308,000	0	0
Quartz Vials:				
Si	32.7	7,250	0	0
Aluminum Foil Capsules:				
AL	4.0	68,000	0	0
Rock and Mineral Grains:				
Si	4.2	1,000	0	0
Al	1.0	17,000	0	0
Fe	1.70	1.27	1.01	0.09
Mg	1.55	8,000	0.0014	0
Ca	1.51	1.80	1.69	1.64
Na	0.21	3,500	0	0
K	0.09	145	0	0
Mn	0.04	18,000	0	0
Co	7×10^{-4}	0.13	0.13	0.13
Sc	6×10^{-4}	2.06	1.84	1.73
Cr	4×10^{-4}	1.07	0.76	0.64
	Total Activity	430,000	5.43	5.05

1 - Data used for activity calculations is listed in Table 1 .

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TABLE 1.

Target element	Atomic mass[1/]	Target isotope	Percent abundance[1/]	Reaction	Product[6/]	Q (MeV)[2/]	Cross section (barns)[3/]	Product half-life[1/]
Na	22.99	^{23}Na	100	n, γ	^{24}Na	+6.96	0.53	15.0 h
Mg	24.31	^{24}Mg	78.7	n, p	^{24}Na	-4.73	0.22	15.0 h
Al	26.98	^{27}Al	100	n, γ	^{28}Al	+7.72	0.21	2.31m
				n, α	^{24}Na	-3.14	0.14	15.0 h
Si	28.09	^{28}Si	92.21	n, p	^{28}Al	-3.86	0.37	2.31m
		^{30}Si	3.09	n, γ	^{31}Si	+6.59	0.11	2.62h
P	30.97	^{31}P	100	n, γ	^{32}P	+7.94	0.19	14.3 d
				n, p	^{31}Si	-0.69	0.14	2.62h
				n, α	^{28}Al	-1.94	0.15	2.31m
S	32.06	^{32}S	95.0	n, p	^{32}P	-0.93	0.30	14.3 d
		^{33}S	0.76	n, p	^{33}P	+0.53	0.015	25 d
		^{34}S	4.22	n, γ	^{35}S	+6.98	0.26	88 d
				n, α	^{31}Si	-1.32	0.14	2.62h
K	39.10	^{41}K	6.88	n, γ	^{42}K	+7.53	1.1	12.4 h
Ca	40.08	^{43}Ca	0.135	n, p	^{43}K	-1.03	(0.1)	22.4 h
		^{44}Ca	2.08	n, γ	^{45}Ca	+7.42	0.67	165 d
		^{48}Ca	0.18	n, γ	^{49}Ca[5/]	+5.14	1.1	8.8 m
Cr	52.00	^{50}Cr	4.31	n, γ	^{51}Cr	+9.25	13.5	27.8 d
Mn	54.94	^{55}Mn	100	n, γ	^{56}Mn	+7.27	13.3	2.58h
Fe	55.85	^{54}Fe	5.82	n, γ	^{55}Fe	+9.30	2.5	2.6 y
				n, p	^{54}Mn	+0.09	0.023	303 d
				n, α	^{51}Cr	+0.84	0.00037	27.8 d
		^{56}Fe	91.66	n, p	^{56}Mn	-2.93	0.00044	2.58h
		^{58}Fe	0.33	n, γ	^{59}Fe	+6.58	0.98	45.1 d
Cu	63.54	^{63}Cu	69.09	n, γ	^{64}Cu	+7.92	4.3	12.9 h
Rb	85.47	^{85}Rb	72.15	n, γ	^{86}Rb	+8.58	0.80	18.8 d
Ti	47.90	^{46}Ti	7.93	n, p	^{46}Sc	-1.58	0.0041	83.8 d
		^{47}Ti	7.28	n, p	^{47}Sc	+0.18	0.00021	3.43d
		^{48}Ti	73.94	n, p	^{48}Sc	-3.21	0.000077	1.83d
Ni	58.71	^{59}Ni	68.27	n, p	^{58}Co	+0.40	0.032	71.3 d
		^{60}Ni	26.10	n, p	^{60}Co	-2.04	0.005	5.26y
		^{62}Ni	3.59	n, α	^{59}Fe	-0.43	0.0057	45.1 d
		^{64}Ni	0.90	n, γ	^{65}Ni	+6.13	1.6	2.52h

1/ Weast (1976). d = days, h = hours, m = minutes

2/ Everling and others (1961).

3/ Koch (1960). Value in parentheses is an estimate.

4/ at 1,000 KW.

5/ Decays to ^{49}Sc, which decays by β^- to ^{49}Ti with a half-life of 57.5d.

6/ Product stable except as noted.