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**Report on Development of Neutron
Passportisation Method**

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Table of contents

Introduction	3
1.Task formulation	5
2.Method description and prototypes review.	7
3.Electronic components of equipment.	16
3.1.The main requirements.	16
3.2.Description of schematics for particular blocks and modules.	17
3.2.1.Detector.	17
3.2.2.Mixer (Fig. 10).	20
3.2.3.Secondary power supply source	20
3.2.4. Amplitude analyser	21
4.Model Monte Carlo calculations.	27
4.1.Calculation model.	27
4.2.Main calculation results.	29
4.3.Some quantitative estimations.	31
5.Some experimental results.	34
5.1.Experimental evaluation of helium tubes characteristics.	34
5.2.Results of model measurements with neutron passportisation system.	36
6.Main conclusions and recommendations.	42
7.Literature.	43
Appendix 1.	44
Appendix 2.	51

Introduction

In this report the results of development of spatial neutron passportisation method are described. The method is aimed on spatial configuration (including the number of sources) control of closed objects containing neutron sources.

The possible areas of method application are:

- the number of warheads control inside the missile heads for RF-US nuclear disarmament treaties verification;
- control of SNM containers arrangement in storage vaults;
- control of complicated assemblies with SNM (and other radioactive materials) to remain unchanged.

For objects with complicated structure such as multiple reentry vehicles the direct interpretation of observed radiation field configuration is rather difficult task. The reconstruction of object structure on basis of radiation field configuration usually require use of external information and is often not obvious. Besides, while using such methods of direct reconstruction of object internal structure the contradiction arises between the requirement of defining sources arrangement (warheads in case of arms control) and requirement of information protection concerning the sources themselves. In this case there may be different limitations on possible spatial resolution of method, use of spectroscopy information, etc.

Thus there exist a need of developing method free of such internal contradictions but still able to reliably insure that inspected object is consistent with its declared features. The method must also be simple in use, portable, applicable in field conditions, versatile (i.e. the same equipment set to be used with different objects).

In this report we describe neutron passportisation method which satisfy (from our point of view) these requirements. The method is based on assumption that the radiation field configuration of the complicated object containing neutron sources remains unchanged until the initial object structure remains the same. For confirmation of radiation field to be unchanged it is sufficient to measure neutron flux in several reference points geometrically strictly connected with object surface. The arrangement of these reference points must be rather uniform along object surface and to be easily reproducible in subsequent measurements. The set of measured values is assumed to be a "passport" of controlled object and is saved as reference set for subsequent checks.

In the first chapter of the report the task is formulated and the possible areas of method application are evaluated.

The second chapter deals with review of existing technique for similar applications, method description, functions of equipment components, principles of measurement procedures (including calibration), and basics of data processing algorithms.

The electronic components of equipment are discussed in the third chapter. The electric circuits and block schemes of components are also presented there.

In the fourth chapter the results of Monte-Carlo simulations of measurement procedures are described. The calculations were performed to preliminary estimate sensitivity of method to changes in model configurations of sources.

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The results of model measurements with neutron passportisation system are presented in the fifth chapter. Here also the results of comparative evaluation of helium tubes of US and RF production are discussed.

The sixth chapter of the report is essentially a resume of main conclusions and recommendations on further development based on the evaluation of experimental device.

The initial raw results of Monte-Carlo calculations are given in Appendix 1 and the list of equipment purchased in frame of the Task Order is given in Appendix 2.

1. Task formulation

In practice of inspection procedures for verification of US-RF START-2 treaty there exists a problem of confirmation of number of warheads in MIRV of ballistic missiles to be consistent with that declared in "Treaty..." documents. At present time solving of this problem is based on visual inspection of missile head interior. The verification process thus include a series of operations needed to prepare the MIRV to demonstration which lead to a large number of transportations and technological difficulties.

It is possible an alternative approach to verification based on implementation of various radiation control means instead of visual inspection.

While developing radiation verification methods not only physical considerations must be taken into account but also concerns of both sides on possible threat to national security interests (the "intrusiveness" problem).

Let's consider several simplified examples. The radiographic methods are obviously inappropriate because "looking through" the missile head will immediately reveal the information about warhead design which is of course unacceptable for both sides in START-2 verification process.

Another quite obvious approach is precise measurements of intrinsic SNM radiation angular distribution around missile heads with subsequent analysis aimed on number of sources determination. In most simple cases such analysis is of no difficulty but even there it may be possible different interpretations. Let's suppose for example that the observed shape of measured angular distribution is of type shown on Fig. 1a.

Different ways of interpreting angular distribution

Fig. 1

For its interpretation there exists at least two possibilities (Fig. 1b & Fig. 1c), where on Fig. 1c possible presence of nonnuclear design elements is shown. In order method be able to distinguish between these (and more complicated) configurations the spatial resolution of detectors must be improved (collimation, use

of nonscattered gamma radiation counting with spectroscopy implementation etc.) This will immediately lead to necessity of precise angular and spatial detector placing (i.e. complicated and precise mechanical devices), complication of measurement methodics, increase in measurement points number. Besides this the improvement of spatial resolution (especially in conjunction with gamma-spectrometry) may allow to define some features of internal structure of sources (i.e. warheads) which is again in contradiction with "intrusiveness" requirements.

Thus at the first glance the method of angular distribution analysis is of no practical importance because of its internal contradiction between reliable interpretation and intrusiveness and also because of need to use complicated mechanical equipment that is not always possible (for example in missile silos). In this case radiation control is not better than visual inspection - one set of difficulties is substituted with another.

Nevertheless, from our point of view there is a possibility of compromise solution which may avoid contradictions and to develop radiation method of verification rather simple and reliable for field applications. Further follows the description of spatial neutron passportisation method proposed as such a solution.

2. Method description and prototypes review.

The basis of method resembles the so called "zero" experiments in physics. It is usually significantly more difficult to measure real value of some characteristic than to notice its discrepancy with assumed (for example theoretical) figure. In case of neutron passportisation method the reference set of neutron flux intensities in definite points of object surface may be used as such an assumed value. This reference set must be measured in course of primer visual inspection for the definite object type. In subsequent inspections the visual control should not be performed and check for object configuration "validity" (the number of sources also) is made by comparison of measurement results in the same set of points as in reference measurements.

For the successful implementation of spatial radiation passportisation method several requirements must be fulfilled. Part of them deal with object properties and part with equipment features and measurement methodics.

The object requirements are:

- the well defined and stable design of objects to be verified (if different objects of the same type are controlled as in case of MIRV) or constant configuration of sources arrangement (if one and the same object is checked at different times as in case of storage vault);
- stability in time (or at least predictable changes) of radiation characteristics of sources.

The equipment and methodics requirements are:

- possibility of reliable reproduction of measurement geometry;
- versatility i.e. possibility of use with objects of different shapes and dimensions;
- simplicity and portability of method;
- absence of external high voltage circuits in order to make possible use in dangerous conditions;
- automated data processing for multiple measurement points;
- possibility of long term information storage.

Several prototypes for the method were estimated in course of literature analysis that have some basic features of discussed method. First of all it must be mentioned the neutron field monitoring system for plutonium storage developed by LANL and tested in ANL West /1/. In that case very similar approach is used for control of neutron field configuration in storage vault with system of 25 stationary placed detectors.

In area of arms control similar solution was implemented in verification procedures for Russian-American Treaty on intermediate and lower range missiles reduction /2/. In this case two types of missiles (with different warheads number) were distinguished by comparing count rates from a single detector placed subsequently in several dozens of points under missile head cover (horizontally oriented). Reproducing of measurement geometry was achieved here by implementation of coordinate grid painted on a textile sheet which was placed in measurement position in a standardised manner.

After analysing requirements for object and equipment the following variant of method was chosen.

The neutron radiation is used as control parameter. The refuse from also possible gamma control option is due to the fact that gamma radiation is more dependable from individual source characteristics (even of the same type) because of impurities may be present. The use of spectroscopy possibilities to avoid influence of this impurities may be unacceptable from the intrusiveness point of view.

The multidetector option was approved with detectors placed on a textile belt with fixed steps. Such a solution makes possible to achieve several purposes simultaneously:

- due to close coincidence of flexible belt with an object surface detectors are always automatically positioned in proper measurement points thus reliably reproducing measuring geometry;
- objects with different shape and dimensions may be controlled by the same equipment;
- the sensor part of equipment may be stored and transported in enrolled form and in field applications does not require complicated mechanical devices.

Different variants of detector system arrangement are illustrated on Fig. 2.

In order to minimise number of cable connections it was proposed to use single cable channel for information collection from all detectors simultaneously. In known variants of multidetector systems it is usually used either "in turn" connection of several detectors to one counting device /3/ or connection of every detector to separate scaler /1,4/. The monochannels for digital information transfer between various devices are also widely used but in this case every sensor must be a sort of complete registration and data processing device. In our case taking into account the overall compactness of system and so far absence of need to transfer information on a long distance it was proposed to use amplitude encoding of output detector pulses.

The output amplitude of pulse from each detector in that case is strictly defined by detector serial number and pulse height analysis is implemented on an input of registration part of system.

The personal computer is used as terminating part of registration system and it is connected with analyser via standard interface RS-232. Computer is also used as controller for system as a whole i.e. it sets measurement time, starts and stops data collection, visualise obtained data. The amplitude "spectrum" from detector system is transferred to a PC and fast diagnostics of system performance may be immediately made.

The controlled parameter is a set of count rates from all the detectors. Before the measurements are performed the calibration procedure must be implemented which is essentially measurement of detectors count rates from the reference neutron source of known yield. All detectors are placed on a circular calibrating device (see Fig. 3) and a source is placed in the center. Calibrating procedure is aimed on accounting to individual values of detector sensitivities and their possible change under environment conditions.

After calibration measurements the adjusting coefficient is calculated for each detector which is equal to ratio of passport yield of neutron source (divided on $4\pi R^2$) to the measured count rate.

Different variants of system arrangement

Fig. 2

Detector arrangement in calibration procedure.

Fig. 3

During actual measurements count rates from each detector are normalised on these coefficients and are stored with corresponding statistic uncertainties.

This measured set of value pairs (normalised count rates with their statistic accuracy) are treated further as spatial neutron passport ("fingerprint") of controlled object.

In verification measurements all the described procedure is repeated in the same order. The measured and reference passports are compared with standard hypothesis test criterion "chi-squared":

$$\chi^2 = \sum_{i=1}^I \frac{(N_i^{(1)} - N_i^{(2)})^2}{(\sigma_i^{(1)2} + \sigma_i^{(2)2})} \leq \chi_{thr}^2, \text{ where}$$

$N_i^{(1)}, N_i^{(2)}$ - detectors count rates in measured and reference passports; $\sigma_i^{(1)}, \sigma_i^{(2)}$ - corresponding statistic errors; χ_{thr}^2 - threshold value of chi-squared distribution for chosen confidence level (90-95%); the number of degrees of freedom is defined by number of detectors.

If the observed value of chi-squared does not exceed threshold value then the hypothesis of object structure to be unchanged is accepted.

The calculation of statistic error for observed count rates (with account on uncertainty in calibration coefficients) is performed according to standard rules:

$$\left(\frac{\sigma(N)}{N}\right)^2 = \left(\frac{\sigma(M)}{M}\right)^2 + \left(\frac{\sigma(k)}{k}\right)^2, \text{ where}$$

M - is measured total number of counts during exposure time; $\sigma(M) = \sqrt{M}$, k - is calibrating coefficient.

The relative error in calibrating coefficient determination is assumed to be equal to relative error in count rate measurement in calibration measurements.

The algorithms of specialised software include procedures of count rate calculations for each detector, determination of calibrating coefficients, passport comparison process, and visualisation of chi-squared test. The additional possibility is search for passport (among stored on disk) most "similar" (from chi-squared point of view) to the current one.

The structural scheme of spatial neutron passportisation system is illustrated on Fig. 4.

Each of twenty detectors is enclosed in cylindrical aluminium shell and consist of:

- thermal neutron helium-3 tube of CW14H type;
- cylindrical polyethylene moderator;
- cadmium filter;
- high voltage converter circuit;
- preamplifier and pulse-shape former.

The sketch drawing of the detector with main dimensions and tube characteristics is presented at Fig. 5.

SYSTEM STRUCTURE

Fig. 4

Detector length - 300mm

Detector diameter - 54mm

Total weight - appr. 1kg

Helium tube characteristics:

Type:	CM14H	
Dimensions:	diameter	-18mm
	active length	-150mm
Filling:	3He	-4atm
	Ar	-3%

Detector design sketch drawing.

Fig. 5

On the flexible textile belt the buffer module is also placed which serves for coupling the output pulse train with cable load.

The belt with detectors and buffer module is a sensor part of system which is connected with registration part and power supply with three-wire cable line (low voltage power, signal, common ground). The registration part of system consists of amplitude analyser and PC.

The arrangement of neutron detectors on a belt is shown on Fig.6.

The secondary power source supplies low voltage DC levels for detector, buffer module, and analyser feeding. The use of rechargeable battery is supposed for field use and AC 220v 50Hz outlet in laboratory applications.

The patent order on method of spatial radiation passportisation and device for its implementation was issued with priority date 08 Aug. 1992 (order number 5064384/25). The Patent service of Russian Federation had made a decision on patent issue. The authors are G.P.Antropov, V.A.Belov, I.E.Mitrofanov, S.F.Razinkov, and S.A.Zykov. The owner of patent and property rights is VNIIEF.

The characteristic (differing from prototypes) features of technical solutions are¹:

Method for control of spatial configuration of radiation sources in closed volumes which include visual inspection of volume interior, differing in that the visual inspection is performed for each object type only once, and before visual inspection (or immediately after it) the measurements of radiation intensity is performed in set of control points strictly connected to object surface, and received set of values is used in subsequent checks as reference for comparison with corresponding values obtained in course of inspection in conditions repeating initial measurements.

The device for method implementation for control of spatial configuration of radiation sources in closed volumes including detection and registration parts connected by cable line, differing in that the detection part is designed as flexible (for example textile) belt on which the detectors are placed with fixed distance from one another, and each of them has differing output pulse amplitude, and the amplitude analyser is used as registration part, and its input is connected to all detectors through one cable.

¹These are given in accordance with patent documentation rules of Russian Federation. The rules require for example the essential description to be a single (even very long) sentence.

Detectors arrangement on textile belt.

Fig. 6

3. Electronic components of equipment.

3.1. The main requirements.

In this chapter the main features of electronic components designed for spatial neutron passportisation method will be discussed.

The main purpose in electronic component design was:

- to obtain information collection from all detectors through single cable;
- to achieve functioning of every detector as autonomous unit;

The specific option of developed system is based on use of neutron counting in neutron monitoring systems but the developed equipment may be implemented without significant changes to any type of primer detectors.

The measurement system detects neutron radiation, transforms it to electrical pulses, encodes detector number by pulse amplitude, and stores pulses in analyser, RAM in a manner that every detector has its own area at an amplitude scale. The information collected in analyser RAM is then transferred to a PC where the data processing may be performed either by standard or specialised software. Initially it was assumed that any pulse height analyser with at least 256 channels and RS-232 PC interface may be used in the system but in particular design the pulse height analyser is a specialised module worked out for the specific system. The PC used as a final device may be of any IBM compatibles with no need of additional modification.

Four major requirements were taken into account in electronic schemes designing:

- reliable performance of all modules in different environment conditions;
- minimised power consumption from primer source;
- minimised size & weight characteristics of modules;
- maximum possible unification of elements for possible interchangeability and use of commercially available units.

The electronic components designed for the system consist of (see Fig. 4):

1. Sensor (detector) including helium tube, preamplifier, amplifier, discriminator-shaper, amplitude coder, and also high voltage converter for tube feeding. Thus detector is a complete detecting and converting block with +12v stabilised power input and pulse output with pulse height determined by detector number.
2. Mixer (buffer module) - performs pulse mixing from all detectors on one load resistor and also couples pulse train of different amplitude with long coaxial cable connecting it with analyser.
3. Amplitude analyser decodes signals, sorts them and also transfers pulse height distribution to PC via RS-232.
4. The secondary stabilised power source works out necessary DC voltage levels for all measurement system and in order to exclude interference and reduce noise problems the power supply for digital and analogue parts of system are made electrically separate.

3.2. description of schematics for particular blocks and modules.

3.2.1. Detector.

The principle electric circuits for components placed in the detector shell are presented at Fig. 7 (amplification part) and Fig. 8 (HV-converter)..

3.2.1.1. The input circuit consists of thermal neutron helium-3 tube CM14H fed through RC filter and load resistor 10Mohm. The HV level is chosen at 1150 ± 50 v providing proportional regime of tube operation.

3.2.1.2. Preamplifier and amplifier are assembled on a single integrated circuit of K584YH1A type which is a pair of low noise operation amplifiers with unipolar feeding +12v. The specifications of this chip are:

-equivalent noise level at input	- 0.7mkv;
-amplification without feedback	- 50000;
-frequency (on unit amplification)	- 20Mhz;
-input resistivity	- 200kohm;
-DC consumption	- 12mA.
-amplification may be changed in wide range.	

3.2.1.3. Discriminator and Pulse shaper of integral type allows to discriminate against noise and to receive at output pulses with standardised shape. Discriminator is assembled on K1401CA chip which is a pair of comparators in one shell.

The discrimination level adjustment is performed while initial detector tuning.

3.2.1.4. Amplitude encoding is achieved by use of four parallel current keys switched to different parts of DC divider through small DIP switches BDM-1-10. Current keys are one integrated CMOS circuit of K561KT3 type. The resistivity of closed key is then about 10ohm and in open state is about several Mohms.

The amplitude of output pulse may be changed in steps of 50mv from 120mv to 1200mv.

3.2.1.5. High voltage converter (Fig. 8).

Taking into account probable applications of method in dangerous conditions there was a need to eliminate external HV circuits, and to place HV converter inside the detector shell.

Presence of individual HV sources in every detector also makes possible to adjust voltage level separately and this is important because of rather wide range of tubes parameters scattering for tubes received from vendor.

The necessity to reduce overall power consumption led to solution to implement the HV converter circuit with initial one-tact generator having large ratio of pulse interval to pulse duration and subsequent voltage multiplication circuit.

The initial generator and pulse shaper is assembled on CMOS chip. Correction of output voltage is achieved by change of initial pulses duration.

The shaped pulses go to buffer cascade which is loaded on primer wiring of pulse transformer.

After eight-times multiplication the output voltage is integrated on a RC filter with large time constant.

DETECTOR MODULE CIRCUIT

FIG 7

F.T.O. 88

Converter design allows to achieve delayed start and smooth (about 10s) rise of high voltage.

In order to improve stability and to reduce level of interfering noise converter feeding is made through input parametric stabiliser.

The resulting power consumption for such a design of HV converter is at level of 30mwatt.

The assembly of all circuits described in 3.2.1.2...3.2.1.5. is performed on four circular metallised plates with 49mm diameter and placed in tail department of detector in form of a "book shelve" (see Fig. 5 and Fig. 9).

The whole assembly is placed in sealed aluminium cylinder protecting detector circuits from moisture.

3.2.2. Mixer (Fig. 10).

Summation of pulses from all 20 detectors is performed on 50ohm loading resistor with subsequent signal power amplification for coupling with long coaxial 50ohm cable. The amplifier is assembled on K547YD1 chip (fast operating amplifier) and two transistors with different resistivity type. The variable resistor in balance circuit is for adjusting zero level of mixer output voltage.

The circuit is assembled on a rectangular metallised plate with dimensions 50x60mm and placed in a sealed metal box with two four pin sockets.

3.2.3. Secondary power supply source (Fig.11).

The power source is built with implementation of two-tact scheme with pulse-width stabilisation of output levels of +12v 1A and +5v 0.6A and parametric stabilisation of other output levels.

The signal from initial generator (IC K155JA3) is scaled by D-trigger for receiving two opposite-phase guiding pulses with interval to pulse duration ratio - 4. These guiding signals are transferred through buffer cascade on power transistors KT908B. Then rectified and filtered voltage from output +12v 1A goes to comparator input and are compared with reference voltage. If output voltage exceeds reference then guiding pulses are rejected and as a result the time of power transistors being open reduces and transferred power reduces also. The change of voltage on +5v output lead to a corresponding change (due to magnetic coupling) of +12v output and this then lead to +5v level stabilisation.

Other stabilisation circuits are assembled with use of K142EH8B chips (parametric voltage stabiliser).

The final characteristics of secondary power supply module are following:

Input voltage:	+(10-16)v
Output levels:	+12v $\pm 0.1\%$ 1A
	-12v $\pm 0.1\%$ 0.1A
	+5v $\pm 0.2\%$ 0.6A
	+12v $\pm 0.1\%$ 0.1A
	-12v $\pm 0.1\%$ 0.1A

The design of scheme is based on a printed circuit plate with dimensions 115x140mm which is placed in metal sealed box with two four-pin sockets.

3.2.4. Amplitude analyser (Fig.12.&Fig.13.)

The input pulse passes through scaling amplifier (1) and after processing in constant level restoring circuit of "time variance" type (2) goes to selecting and storing device (3) functioning as pulse duration prolongator. The ADC of sequential comparison type (4) converts pulse amplitude into a digital code, which forms address for RAM (6) through multiplexor (5).

The processor chip of type i8035 (7) reads byte from RAM according to the address, increments it and again writes to RAM with the same address.

Processor has a possibility to access RAM through multiplexor (5) and to transfer its contents via RS-232 port. The exchange with main computer is performed on a command level with use of specially designed protocol. Processor also synchronises regimes of selection, storage and processing of information through driving device (9).

On a software level processor guides all analogue elements of the module such as constant level restorer (2), selection-storing device (3), ADC (4).

Analyser is designed as a single printed circuit module placed in metal sealed box.

Neutron detector design.

Fig. 9

ADC BLOCK (STRUCTURE CIRCUIT)

Fig. 12

Fig. 13

4. Model Monte Carlo calculations.

4.1. Calculation model.

The model Monte Carlo calculations were performed with "C-60" computer code and neutron constants set "BAS".

The basic purpose of calculations was to simulate a radiation control situation for neutron sources configuration in a cylindrical closed volume. The geometry was chosen to be similar to that in a number of warheads verification under missile head cover.

Of course calculations are of illustrative character and does not reflect any specific real characteristics of actual weapon design.

The main source of neutrons in plutonium is ^{240}Pu isotope /5/. Supposing for our model presence of only two isotopes ^{239}Pu and ^{240}Pu and content of the later to be 6% /5,6/ we receive the specific yield of 61100n/s.kg for dispersed mass (without multiplication and self-attenuation).

The source model used in calculations is a hollow plutonium sphere with 4kg mass and 5cm outer radius. This sphere is placed into a cylindrical container with steel and polyethylene walls (see Fig. 14).

Fig 14.

Source model used in calculations

This sources of this type were then placed (from two to seven in number) uniformly on a circle with 1500mm radius. One of the sources may be placed also in the center of circle.

Neutron detectors were placed uniformly on circle 2000mm radius with the same center as sources configuration.

The geometry of sources and detector arrangement is illustrated on Fig. 15.

Fig. 15

Monte Carlo calculations geometry.

Various calculated patterns differ in number of sources placed on a circle and in the center. In points where detectors were located neutron fluxes normalised on one neutron born in the system were calculated. The sketch of calculated patterns and corresponding numbers of computer runs are presented in Table 4.1. In the table asterisks (*) designate containers with plutonium and zeros (0) designate empty containers.

Table 4.1.

6000	6002	6004	6006	6009	6011
		*	*	*	0
	*			* *	* *
* *		* *	* * *	*	*
	* *			* *	* *
		*	*	*	*
6001	6003	6005	6007	6010	6008
		0	*	*	0
	0			* *	
* 0		* *	* 0 *	0	* * *
	* *			* *	
		*	*	*	*

The symmetry properties of patterns allowed to calculate neutron fluxes not in all set of points but only in part of them and this was actually used in real calculations. This approach makes possible to reduce processor time without decrease in statistic accuracy of final results.

The neutron spectrum (see Table 4.2.) used in calculations was assumed to be of fission type /7/. and source density was uniform through plutonium sphere. Thermal energy corresponded to 1/40ev.

Table 4.2.

Energy range (Mev)	Fraction
10.5...6.5	0.020
6.5...4.0	0.098
4.0...2.5	0.190
2.5...1.4	0.268
1.4...0.8	0.196
0.8...0.4	0.135
0.4...0.2	0.058
0.2...0.1	0.022
0.1...0.0465	0.009
0.0465...0.0215	0.003
0.0215...0.1	0.001

4.2. Main calculation results.

The neutron fluxes in detector location points were calculated for all patterns from table 4.1. The statistic accuracy was about 2% for all cases.

From the mathematical point of view the calculated values (if statistic uncertainty becomes infinitely small) may be treated as probability distribution functions (with appropriate normalisation) for neutrons entering detectors. The count rate of a detector located in this point will be proportional to this probability.

On practice the task of distinguishing different patterns in neutron passportisation method will be solved by implementation of hypothesis check test on that two corresponding distributions of count rates are the same. Thus the simulating calculations purposes may be defined as following:

- to check the initial difference in probability distribution functions received by Monte Carlo simulation for model configurations of sources;
- the quantitative estimation of needed exposure time for measuring count rates to receive these distributions with necessary statistic accuracy.

The solution of the first task is achieved by implementation of chi-squared test to calculated distributions i.e. evaluation of:

$$\chi^2 = \sum_{i=1}^l \frac{(N_i^{(1)} - N_i^{(2)})^2}{(\sigma_i^{(1)})^2 + (\sigma_i^{(2)})^2}, \text{ where } N_i^{(1,2)} - \text{calculated flux values for } i\text{-th}$$

detector, and $\sigma_i^{(1,2)}$ -corresponding statistic errors of calculation,

and its comparison with threshold chi-squared value for $l=20$ degrees of freedom and chosen confidence level.

The raw calculation results are presented in Appendix 1 (Tables A1.1...A1.12) for all source patterns, and results of χ^2 -testing of these distributions are given in Table 4.3

Table 4.3.

Results of χ^2 -testing of flux distributions from different source patterns. The threshold criterion value for 20 degrees of freedom and 95% confidence level is 31.4

	x o	x	o	x	o	x	x	o	x	x	o
		x x	x x	x x	x x	xxx	xox	xxx	x x	x x	x x
				x	x	x	x	x	x	o	x
									x x	x x	x x
									x	x	x
x x	42710	18278	31840	20644	20436	26261	21176	19859	59949	54278	36484
	x o	35809	50019	44169	38742	51253	43216	37430	92206	86339	56834
		x									
		x x	11376	11196	11679	12996	11198	10235	31949	27990	18996
			o								
			x x	27889	12534	31781	27050	17051	59379	54690	31769
				x							
				x x	7669	1155	57	5069	18726	15365	10919
				x							
					o						
					x x	11385	7653	1623	39023	35003	16841
					x						
						x					
						xxx	769	7057	13080	10481	8241
						x					
						xox					
						x	4976	17179	14152	10065	
							o				
							xxx	30836	27390	11024	
							x				
								x			
								x x	470	6981	
								x			
								x x			
								o			
								x x			
								x			
											6657

The results presented in the table show that all calculated patterns are distinguishable. Thus these results may be used for estimations of practical applicability of method.

During real measurements the observed count rates must be measured with certain statistic precision i.e. corresponding total

number of counts must be obtained in order to distinguish patterns with used criterion. Thus the needed counting statistics are defined by degree of difference in compared distributions and calculated values will be used as such distributions.

4.3. Some quantitative estimations.

4.3.1. As a first example let's consider a situation when it is necessary to distinguish between one and the same source pattern but with different specific neutron yield for source. In practical application it may be a model for removing part of material from each container.

Let's suppose then that both configurations are measured for time period providing equal relative statistic accuracy (δ). The sources yields will be n_1 и n_2 respectively, and $P_i^{(1)}, P_i^{(2)}$ - corresponding probabilities of neutron detection in detectors location ($P_i^{(1)}, P_i^{(2)}$ are proportional to calculated values from tables A1.1....A1.12.).

Then the criterion may be rewritten as:

$$\chi^2 = \sum_i \frac{(N_i^{(1)} - N_i^{(2)})^2}{D(N_i^{(1)} - N_i^{(2)})} = \frac{l \left(1 - \frac{n_2}{n_1}\right)^2}{\sigma^2 \left(1 + \left(\frac{n_2}{n_1}\right)^2\right)} \geq \chi_{thr}^2(l) ,$$

where $N_i^{(1,2)} = P_i \cdot n_{(1,2)}$ - count rates (registration efficiency not accounted for here) for each of l detectors. The resulting

quadratic equation may be resolved in respect to ratio $\frac{n_1}{n_2}$ at

different values of δ and this makes possible to predict limit to distinguishable ratio value at given relative statistic accuracy.

Interpolation of equation solutions in range $0 \leq \delta \leq 15\%$ gives the following relationship:

$\frac{n_2}{n_1} \approx 1 \pm 0.021 \cdot \delta(\%)$, i.e. if passport measurements are performed with statistic accuracy 5% then it is possible to notice approximately 9% change in source specific yield.

4.3.2. the next example deals with situation when patterns with different number and arrangement of sources with equal specific yield must be distinguished.

In this case criterion may be converted (again assuming equal relative statistic accuracy δ) to:

$$\chi^2 = \frac{1}{\delta^2} \cdot \sum_i \left\{ 1 + 2 \frac{N_i^{(1)} \cdot N_i^{(2)}}{(N_i^{(1)})^2 + (N_i^{(2)})^2} \right\} \geq \chi_{thr}^2, \text{ or taking into account}$$

that $N_i^{(1,2)} = P_i^{(1,2)} \cdot n$:

$$\sum_i \frac{P_i^{(1)} \cdot P_i^{(2)}}{(P_i^{(1)})^2 + (P_i^{(2)})^2} \leq \frac{1}{2} \{ 1 - \chi_{thr}^2(l) \cdot \delta^2 \},$$

this expression allow to estimate statistic accuracy of passport measurements needed to find difference between similar sources configurations. Thus for example for patterns 6004 and 6007 (see Table 4.1) such an estimation gives $\delta = 2.5\%$ i.e. in order to distinguish patterns differing in presence of extra empty container measurements must be done not worse than with pointed statistic accuracy.

In practical applications the most interesting variants are of course those of types similar to 6009&6010 i.e. differing in sources number. For majority of such configurations it is sufficient to measure passports with 5-10% statistics.

The above estimations deal only with statistic errors, in practical applications it is of course important to have sources yield uncertainties and equipment stability not worse than measurement statistic accuracy.

4.3.3. As a next step it will be useful to evaluate time of measurement needed to distinguish some of calculated source patterns. For this evaluation we'll suppose that patterns are measured for the same time and counting statistics follow Poisson distribution, i.e. dispersion D of total number of counts equals this number itself. Besides this for such an evaluation we must estimate intrinsic efficiency (ε) of the detectors with respect to neutron flux. The registration efficiency depends on neutron spectrum and on the degree of spectrum shape change due to presence of scatters and moderators. In course of this work the number of (n,p) reactions in detector tubes was calculated by Monte Carlo method for several variants of measurement system arrangement (detectors on calibrating ring, detectors "hanging" in air, detectors near the concrete floor etc.). In order to use in formulas the number of counts the value of $N_i = P_i \cdot n$ must be multiplied on measurement time t and effective detector sensitivity $\varepsilon \cdot S$, i.e. intrinsic efficiency by effective detector surface area. In calculations the value for $\varepsilon \cdot S$ was in range 0.5...1.3 pulse·cm²/n and in further estimations the intermediate value 0.9 pulse·cm²/n will be used.

The chi-squared criterion in this case may be written as:

$$\chi^2 = t \cdot N_0 \cdot \varepsilon \cdot S \cdot \sum_i \frac{(P_i^{(1)} \cdot k_1 - P_i^{(2)} k_2)^2}{(P_i^{(1)} \cdot k_1 + P_i^{(2)} k_2)} \geq \chi_{thr}^2,$$

where $N_0 = 244400 \text{ n/s}$ is source yield, $k_{1,2}$ - number of sources in pattern.

Then for needed measurement time we have:

$$t \geq \frac{\chi_{thr}^2}{\varepsilon SN_0} \cdot \left(\sum_i \frac{(P_i^{(1)} \cdot k_1 - P_i^{(2)} \cdot k_2)^2}{P_i^{(1)} \cdot k_1 + P_i^{(2)} \cdot k_2} \right)^{-1},$$

and after substituting calculated values for P_i from tables Appendix 1 we receive for example that configurations 6004&6007 may be distinguished after app. 300s exposition, and for patterns 6009&6010 it is sufficient about 60s measurement time.

4.3.4. For practical applications it is also interesting possible error in detector positioning which may lead to mistake in passport comparison. This may be estimated on a following model.

Let one and the same pattern to be measured twice with the same statistic accuracy, and detector arrangement shifted around the axis on a definite angle. for estimation we accept that shift angle is not more than angular distance between detectors and P_i values may be determined by linear interpolation of calculated values.

The distinguish criterion in this case gives:

$$\chi^2 = \frac{1}{\delta^2} \cdot \sum_i \frac{\left(\frac{\varphi_1}{\varphi_0} \right)^2 (P_{i+1}^{(1)} - P_i^{(1)})^2}{(P_i^{(1)})^2 + \left\{ P_i^{(1)} + \frac{\varphi_1}{\varphi_2} (P_{i+1}^{(1)} - P_i^{(1)}) \right\}^2} \geq \chi_{thr}^2(l) = 31.4,$$

where φ_1, φ_0 -angle shift and initial angular distance between detectors.

It is obvious that more symmetric patterns must allow greater shift, thus for illustration purposes we'll give estimated values for configurations 6001 and 6009. In Table 4.4 the χ^2 values at different shift angles are given for this patterns.

Table 4.4.

χ^2				
angle	6001		6009	
	$\delta 2=5\%$	$\delta 2=10\%$	$\delta 2=5\%$	$\delta 2=10\%$
3°	112	28.1	20.6	0.54
6°	555	139	87.7	21.9
9°	1247	312	211	52.7
12°	1903	476	400	100
15°	2457	614	665	166
18°	2920	730	1010	252

Thus the estimation gives that in course of measurements with "good" symmetry and counting statistics at 5% level it is necessary to position detectors with about 3° angular precision (6° at 10% level) while for patterns with worse symmetry detector placing precision must be sufficiently better and to be not more than 3° even in measurements with 10% statistic accuracy.

5. Some experimental results.

5.1. Experimental evaluation of helium tubes characteristics.

5.1.1. The purpose of this part of work was to compare main features of helium-3 tubes manufactured in RF and USA, and also to estimate repeatability of tubes characteristics in a batch received for passportisation system assembly.

The measurements were performed on twelve "TEXLIUM" tubes received from LANL and fifty tubes of CM14H type manufactured in RF.

The controlled parameters were following:

- plateau slope of counting curve;
- scattering of gas amplification coefficients in the batch;
- neutron count rates and background count rates in fixed geometry conditions.

The results were used also for determination of optimum regime of CM14H operation and selection of twenty tubes from the batch for system assembly.

5.1.2. Measurement geometry and equipment.

The Pu-Be neutron source with yield $1.15 \cdot 10^6$ n/s placed in 175mm diameter polyethylene sphere (internal diameter-75mm) was located at 800mm distance from horizontally oriented counter at 1200mm height from concrete floor.

To estimate sensitivity of tubes to gamma rays they were irradiated with ^{147}Cs source with yield 10^5 γ /s.

The AMPTEK PCB modules received from LANL were used as preamplifiers, spectroscopy line and ADC in CAMAC standard, and PC-286 were used for data processing.

The signal for pulse height analysis was taken from TP1 point of AMPTEK circuit.

5.3.1. Measurements and main results.

For TEXLIUM tubes and CM14H ones there were measured count rate dependencies on HV level of tube anode at discrimination level defined in accordance with item D of "AMPTEK Calibration Procedures" manual. The HV level corresponding to a middle point of plateau was chosen.

The pulse height distributions were measured for different values of spectrometer time constant (in range 1...7mks) in order to obtain optimum value corresponding to minor width of full energy peak.

The spectrograms of pulses were again measured at different HV levels for fine tuning of its value at chosen time constant.

At previously defined discrimination level the sensitivity of tubes to gamma irradiation was estimated.

Pulse height spectra was also measured at optimum values of HV and T for all tubes in the batch to estimate gas amplification coefficient scattering for different tubes.

In conditions described in item 5.1.2. count rates and background count rates were measured.

On Fig.16 and 17 spectrograms of output pulses are illustrated for TEXLIUM and CM14H tubes.

Fig. 16.

Fig. 17.

5.1.4. The main results on tubes evaluation.

The analysis of obtained results leads to following conclusions.

On TEXLIUM tubes:

The estimated batch has rather low scattering of characteristics (relative range of gas amplification coefficients is not more than 5%, of count rates in fixed conditions - not more than 3%, plateau slope is not more than 2%/100v for all tubes) which makes it easy to use such tubes in multidetector systems.

On CW14H tubes:

Taking into account the supposed conditions of system operation (comparatively low count rates and gamma background presence) the optimum performance parameters are estimated to be following: HV level- 1150 ± 50 v, T - 6mks. Scattering of gas amplification coefficients and count rates is much more significant for this type of tubes and is about 16% and 18% respectively. The tube sensitivity (related to a unit of tube length is also lower in comparison with TEXLIUM tubes for about 20-30% due to their less thickness.

The sensitivity to gamma rays is slightly less for CW14H tubes perhaps due to their thinner walls and lower Ar pressure.

The short plateau distance for this tubes may perhaps be explained by lower diameter and nonuniformities in anode wire thickness.

5.2. Results of model measurements with neutron passportisation system.

5.2.1. The preliminary test for method performance was made with Pu-Be neutron sources with yields in range of $(4.72 \dots 5.55) \cdot 10^5$ n/s.

The sources were placed inside the calibrating device described in chapter 2. For illustrative purposes there were considered two basic initial configurations of sources:

- four sources arranged uniformly on a circle with 300mm radius;
- six sources placed uniformly on the same radius and one more source in the circle center.

During further measurements different perturbations were applied to base configurations and passport measurements were performed to find difference with χ^2 -criterion.

The output information for the system is histogram of measured and reference count rates from detectors and obtained actual value of χ^2 for compared pair. The threshold value for 20 degrees of freedom and 95% confidence level (5% probability of first type mistake) is 31.4.

Table 5.1. illustrates the form of spatial neutron passport stored on PC disk for future use in comparison.

Table 5.1.

Text·comment →	06 September 1994 7 sources.		
Number of points in passport→	20		
Point numbers↓	0	46.996	0.03335
	1	47.482	0.03339
	2	42.093	0.03322
	3	46.302	0.03149
	4	47.010	0.03187
	5	42.094	0.03187
	6	40.891	0.03207
	7	43.174	0.03232
	8	40.921	0.03387
	9	40.142	0.02731
	10	42.030	0.02918
	11	40.766	0.03305
	12	38.424	0.03190
	13	41.545	0.03329
	14	43.819	0.03336
	15	40.173	0.03698
	16	42.770	0.03342
	17	48.235	0.03682
	18	46.930	0.03253
	19	38.749	0.03513
	↑ count rates (rel.units)		↑ relat. stat. error

The results of comparison of measured and reference data for base configurations and some their disturbances are presented at Fig. 18...23. The schematic sketches of compared patterns are also illustrated on that drawings.

$$\chi^2=551$$

Comparison of patterns * * & * 0

* * * *

In base configuration of four sources one is removed.

Fig.18

$$\chi^2=275$$

Comparison of patterns * * & **

* *

In four-source base configuration the sources are shifted to center by half of initial radius.

Fig. 19

$\chi^2=126$

Comparison of patterns * * & * *

* * *

* * * 0 *

* *

Central source is removed from basic configuration of seven sources.

Fig. 20

$\chi^2=394$

Comparison of patterns * * & * 0

* * *

* * *

* *

Peripheral source is removed from basic configuration of seven sources.

Fig.21

$$\chi^2=39$$

Comparison of patterns

* * & * *
 * * * * * ⊕ *
 * * * *

Polyethylene hemisphere (175mm outer diameter and 75mm inner diameter) is introduced in basic configuration of seven sources.

Fig. 22

$$\chi^2=11.2$$

Comparison of pattern * * with the same in repeated measurement.

* * *
 * *

Fig. 23

For all examples given on Fig.18...23 the statistic accuracy of performed measurements was at level 2-4%. Such level for described geometry and mentioned sources was achieved in time periods 10-20s.

The results of model measurements show that all described patterns are reliably differing from one another to be distinguished with passportisation method. The minimum difference was observed in case of introducing additional scattering object in basic configuration. But even in this case it was possible to notice difference corresponding to presence of polyethylene with app. 1kg mass at this (rather low) level of counting statistics.

The model measurements allow also to estimate the real sensitivity of detectors to Pu-Be spectrum in described conditions. The sensitivity value equal to effective detector surface area multiplied by intrinsic efficiency ($S \cdot \varepsilon$) may be used in future for estimation of count rate for detector placed in known neutron flux.

In above measurements the equivalent value of ($S \cdot \varepsilon$) was estimated to be (1.2...1.4)puls. $\cdot$ cm²/n for different detectors.

This value of course must be treated only as rough estimate because for the detector design used here this parameter should depend on spectrum type and presence of scatters and moderators near measurement position. For practical applications such a dependence lead to necessity of performing passport measurements only in strictly defined conditions. We think that for probable areas of method application (arms control and storage monitoring) this requirement may be easily satisfied.

6. Main conclusions and recommendations.

In course of work on contract 0002P0004-95 (Task order 004) the practical method of neutron passportisation was developed for sources configuration control in close volumes.

The applicability of method was preliminary checked on model configuration and developed supplement technological equipment allow its use in field applications.

The basic characteristic features of method are following:

- implementation of multidetector scheme of sensing part;
- use of internal HV converters for possible method implementation in dangerous conditions;
- collection of information from all detectors through one cable due to use of output pulse amplitude coding of detector number;
- arrangement of detectors on flexible textile belt providing reliable reproducibility of measurement geometry in field applications and possibility of the same equipment to be used on objects of different shape and dimensions;
- use of any IBM-compatible PC for measurement system driving, data processing, and information storage;
- implementation of calibration procedure for accounting of individual detector features;
- use of statistic hypothesis test for passport measurements analysis.

The most probable areas of method application are:

- control of warheads number in missile heads and on transportation vehicles for verification procedures of Russian-American nuclear disarmament treaties;
- control of plutonium containers arrangement to be unchanged in storages;
- control of internal configuration of any complex objects containing SNM;
- radiation monitoring of production sites and technology processes (after further software development).

The first priority tasks for further method development and its promotion to practical applications are considered to be following:

- proceeding in method equipment design in order to make possible its commercialisation and manufacturing in factory (non laboratory) conditions;
- testing of prototype system in various environment conditions, testing of performance stability, test of field application technology;
- familiarisation of possible users in RF and USA with development results in order to estimate probability of future practical applications.

7.Literature.

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Appendix 1.

In the appendix the raw data of Monte Carlo calculations are given in Tables A1.1....A1.12 for source patterns described in chapter 4 of the report.

The data in tables are normalised by one neutron entering the system.

Table A1.1

Neutron fluxes n/cm²s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6000 container pattern:

* *

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
2.3765e-000	1.8000e+000	2.2715e-005	1.8000e+000
1.1045e-005	1.5000e+000	1.0570e-005	1.5000e+000
4.4310e-006	1.3000e+000	4.2605e-006	1.3000e+000
2.5235e-006	1.2000e+000	2.4290e-006	1.2000e+000
1.8535e-006	1.0000e+000	1.7855e-006	1.0000e+000
1.6900e-006	9.0000e-001	1.6240e-006	9.0000e-001
1.8535e-006	1.0000e+000	1.7855e-006	1.0000e+000
2.5235e-006	1.2000e+000	2.4290e-006	1.2000e+000
4.4310e-006	1.3000e+000	4.2605e-006	1.3000e+000
1.1045e-005	1.5000e+000	1.0570e-005	1.5000e+000
2.3765e-005	1.8000e+000	2.2715e-005	1.8000e+000
1.1045e-005	1.5000e+000	1.0570e-005	1.5000e+000
4.4310e-006	1.3000e+000	4.2605e-006	1.3000e+000
2.5235e-006	1.2000e+000	2.4290e-006	1.2000e+000
1.8535e-006	1.0000e+000	1.7855e-006	1.0000e+000
1.6900e-006	9.0000e-001	1.6240e-006	9.0000e-001
1.8535e-006	1.0000e+000	1.7855e-006	1.0000e+000
2.5235e-006	1.2000e+000	2.4290e-006	1.2000e+000
4.4310e-006	1.3000e+000	4.2605e-006	1.3000e+000
1.1045e-005	1.5000e+000	1.0570e-005	1.5000e+000

Table A1.2

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6001 container pattern:

* 0

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
4.6390e-005	1.5000e+000	4.4180e-005	1.4000e+000
2.0730e-005	1.3000e+000	1.9870e-005	1.3000e+000
7.6820e-006	1.2000e+000	7.3880e-006	1.2000e+000
3.9470e-006	1.1000e+000	3.8030e-006	1.0000e+000
2.3780e-006	1.1000e+000	2.2940e-006	1.1000e+000
1.6830e-006	1.1000e+000	1.6190e-006	1.1000e+000
1.3300e-006	1.1000e+000	1.2800e-006	1.1000e+000
1.0900e-006	1.2000e+000	1.0460e-006	1.1000e+000
9.4830e-007	1.1000e+000	9.1370e-007	1.1000e+000
8.8510e-007	1.2000e+000	8.4880e-007	1.1000e+000
2.4040e-007	1.2100e+000	2.3750e-007	1.2200e+000
8.8510e-007	1.2000e+000	8.4880e-007	1.1000e+000
9.4830e-007	1.1000e+000	9.1370e-007	1.1000e+000
1.0900e-006	1.2000e+000	1.0460e-006	1.1000e+000
1.3300e-006	1.1000e+000	1.2800e-006	1.1000e+000
1.6830e-006	1.1000e+000	1.6190e-006	1.1000e+000
2.3780e-006	1.1000e+000	2.2940e-006	1.1000e+000
3.9470e-006	1.1000e+000	3.8030e-006	1.0000e+000
7.6820e-006	1.2000e+000	7.3880e-006	1.2000e+000
2.0730e-005	1.3000e+000	1.9870e-005	1.3000e+000

Table A1.3

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6002 container pattern:

*

* *

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
7.9217e-006	1.8000e+000	1.5417e-005	2.8000e+000
3.6817e-006	1.5000e+000	7.1400e-006	2.1000e+000
1.4770e-006	1.3000e+000	3.2670e-006	1.6000e+000
8.4117e-007	1.2000e+000	2.3853e-006	1.3000e+000
6.1783e-007	1.0000e+000	2.5337e-006	1.4000e+000
5.6333e-007	9.0000e-001	4.0233e-006	1.6000e+000
6.1783e-007	1.0000e+000	1.0167e-005	2.4000e+000
8.4117e-007	1.2000e+000	1.3237e-005	2.3000e+000
1.4770e-006	1.3000e+000	5.2967e-006	1.8000e+000
3.6817e-006	1.5000e+000	2.8600e-006	1.5000e+000
7.9217e-006	1.8000e+000	2.3570e-006	1.3000e+000
3.6817e-006	1.5000e+000	2.8600e-006	1.5000e+000
1.4770e-006	1.3000e+000	5.2967e-006	1.8000e+000
8.4117e-007	1.2000e+000	1.3237e-005	2.3000e+000
6.1783e-007	1.0000e+000	1.0167e-005	2.4000e+000
5.6333e-007	9.0000e-001	4.0233e-006	1.6000e+000
6.1783e-007	1.0000e+000	2.5337e-006	1.4000e+000
8.4117e-007	1.2000e+000	2.3853e-006	1.3000e+000
1.4770e-006	1.3000e+000	3.2670e-006	1.6000e+000
3.6817e-006	1.5000e+000	7.1400e-006	2.1000e+000

Table A1.4

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6003 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
2.3275e-007	2.0300e+000	2.2615e-007	2.0800e+000
1.1390e-006	1.7000e+000	1.0995e-006	1.7000e+000
1.3810e-006	1.4000e+000	1.3235e-006	1.3000e+000
1.8220e-006	1.4000e+000	1.7510e-006	1.4000e+000
2.7865e-006	1.7000e+000	2.6840e-006	1.7000e+000
5.6050e-006	1.9000e+000	5.3850e-006	1.9000e+000
1.5515e-005	2.1000e+000	1.4895e-005	2.1000e+000
2.0425e-005	2.3000e+000	1.9570e-005	2.3000e+000
8.0350e-006	1.9000e+000	7.7100e-006	1.8000e+000
4.0800e-006	1.4000e+000	3.9155e-006	1.4000e+000
3.2610e-006	1.3000e+000	3.1285e-006	1.3000e+000
4.0800e-006	1.4000e+000	3.9155e-006	1.4000e+000
8.0350e-006	1.9000e+000	7.7100e-006	1.8000e+000
2.0425e-005	2.3000e+000	1.9570e-005	2.3000e+000
1.5515e-005	2.1000e+000	1.4895e-005	2.1000e+000
5.6050e-006	1.9000e+000	5.3850e-006	1.9000e+000
2.7865e-006	1.7000e+000	2.6840e-006	1.7000e+000
1.8220e-006	1.4000e+000	1.7510e-006	1.4000e+000
1.3810e-006	1.4000e+000	1.3235e-006	1.3000e+000
1.1390e-006	1.7000e+000	1.0995e-006	1.7000e+000

Table A1.5

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6004 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.3353e-005	2.5000e+000	1.2598e-005	2.5000e+000
6.0800e-006	2.0000e+000	5.8625e-006	2.0000e+000
3.3950e-006	1.4000e+000	3.2700e-006	1.4000e+000
3.4600e-006	1.3000e+000	3.3325e-006	1.3000e+000
6.0850e-006	2.0000e+000	5.8575e-006	2.0000e+000
1.2938e-005	2.4000e+000	1.2488e-005	2.3000e+000
6.0850e-006	2.0000e+000	5.8575e-006	2.0000e+000
3.4600e-006	1.3000e+000	3.3325e-006	1.3000e+000
3.3950e-006	1.4000e+000	3.2700e-006	1.4000e+000
6.0800e-006	2.0000e+000	5.8625e-006	2.0000e+000
1.3353e-005	2.5000e+000	1.2598e-005	2.5000e+000
6.0800e-006	2.0000e+000	5.8625e-006	2.0000e+000
3.3950e-006	1.4000e+000	3.2700e-006	1.4000e+000
3.4600e-006	1.3000e+000	3.3325e-006	1.3000e+000
6.0850e-006	2.0000e+000	5.8575e-006	2.0000e+000
1.2938e-005	2.4000e+000	1.2488e-005	2.3000e+000
6.0850e-006	2.0000e+000	5.8575e-006	2.0000e+000
3.4600e-006	1.3000e+000	3.3325e-006	1.3000e+000
3.3950e-006	1.4000e+000	3.2700e-006	1.4000e+000
6.0800e-006	2.0000e+000	5.8625e-006	2.0000e+000

Table A1.6

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6005 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.2627e-006	2.6000e+000	1.2217e-006	2.7000e+000
1.2473e-006	2.1000e+000	1.1873e-006	2.0000e+000
2.0777e-006	1.6000e+000	1.9947e-006	1.6000e+000
3.3367e-006	2.0000e+000	3.1977e-006	2.0000e+000
7.3433e-006	2.6000e+000	7.0267e-006	2.6000e+000
1.6500e-005	2.9000e+000	1.5590e-005	2.9000e+000
7.9567e-006	2.1000e+000	7.7133e-006	2.1000e+000
4.2833e-006	1.7000e+000	4.1233e-006	1.6000e+000
4.3700e-006	1.6000e+000	4.1967e-006	1.5000e+000
7.7067e-006	2.3000e+000	7.4433e-006	2.3000e+000
1.6950e-005	2.9000e+000	1.6350e-005	2.9000e+000
7.7067e-006	2.3000e+000	7.4433e-006	2.3000e+000
4.3700e-006	1.6000e+000	4.1967e-006	1.5000e+000
4.2833e-006	1.7000e+000	4.1233e-006	1.6000e+000
7.9567e-006	2.1000e+000	7.7133e-006	2.1000e+000
1.6500e-005	2.9000e+000	1.5590e-005	2.9000e+000
7.3433e-006	2.6000e+000	7.0267e-006	2.6000e+000
3.3367e-006	2.0000e+000	3.1977e-006	2.0000e+000
2.0777e-006	1.6000e+000	1.9947e-006	1.6000e+000
1.2473e-006	2.1000e+000	1.1873e-006	2.0000e+000

Table A1.7

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6006 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.0140e-005	2.5000e+000	9.6800e-006	2.5000e+000
5.4300e-006	2.0000e+000	5.1740e-006	2.0000e+000
3.3680e-006	1.2000e+000	3.2140e-006	1.2000e+000
3.3980e-006	1.3000e+000	3.2400e-006	1.3000e+000
5.3560e-006	1.9000e+000	5.0700e-006	1.8000e+000
1.0608e-005	2.8000e+000	9.9200e-006	2.7000e+000
5.3560e-006	1.9000e+000	5.0700e-006	1.8000e+000
3.3980e-006	1.3000e+000	3.2400e-006	1.3000e+000
3.3680e-006	1.2000e+000	3.2140e-006	1.2000e+000
5.4300e-006	2.0000e+000	5.1740e-006	2.0000e+000
1.0140e-005	2.5000e+000	9.6800e-006	2.5000e+000
5.4300e-006	2.0000e+000	5.1740e-006	2.0000e+000
3.3680e-006	1.2000e+000	3.2140e-006	1.2000e+000
3.3980e-006	1.3000e+000	3.2400e-006	1.3000e+000
5.3560e-006	1.9000e+000	5.0700e-006	1.8000e+000
1.0608e-005	2.8000e+000	9.9200e-006	2.7000e+000
5.3560e-006	1.9000e+000	5.0700e-006	1.8000e+000
3.3980e-006	1.3000e+000	3.2400e-006	1.3000e+000
3.3680e-006	1.2000e+000	3.2140e-006	1.2000e+000
5.4300e-006	2.0000e+000	5.1740e-006	2.0000e+000

Table A1.8

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6007 container pattern:

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E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.2000e-005	2.6000e+000	1.1520e-005	2.5000e+000
6.0100e-006	2.0000e+000	5.7625e-006	2.0000e+000
3.5875e-006	1.5000e+000	3.4475e-006	1.4000e+000
3.5500e-006	1.3000e+000	3.4125e-006	1.3000e+000
6.2125e-006	2.0000e+000	5.9675e-006	2.0000e+000
1.2960e-005	2.4000e+000	1.2445e-005	2.4000e+000
6.2125e-006	2.0000e+000	5.9675e-006	2.0000e+000
3.5500e-006	1.3000e+000	3.4125e-006	1.3000e+000
3.5875e-006	1.5000e+000	3.4475e-006	1.4000e+000
6.0100e-006	2.0000e+000	5.7625e-006	2.0000e+000
1.2000e-005	2.6000e+000	1.1520e-005	2.5000e+000
6.0100e-006	2.0000e+000	5.7625e-006	2.0000e+000
3.5875e-006	1.5000e+000	3.4475e-006	1.4000e+000
3.5500e-006	1.3000e+000	3.4125e-006	1.3000e+000
6.2125e-006	2.0000e+000	5.9675e-006	2.0000e+000
1.2960e-005	2.4000e+000	1.2445e-005	2.4000e+000
6.2125e-006	2.0000e+000	5.9675e-006	2.0000e+000
3.5500e-006	1.3000e+000	3.4125e-006	1.3000e+000
3.5875e-006	1.5000e+000	3.4475e-006	1.4000e+000
6.0100e-006	2.0000e+000	5.7625e-006	2.0000e+000

Table A1.9

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6008 container pattern:

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E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.1623e-006	5.9000e+000	1.0798e-006	4.5000e+000
1.5405e-006	1.7000e+000	1.4820e-006	1.7000e+000
2.1823e-006	1.4000e+000	2.1023e-006	1.4000e+000
3.1200e-006	1.7000e+000	3.0125e-006	1.7000e+000
6.0250e-006	2.4000e+000	5.8250e-006	2.5000e+000
1.2398e-005	3.3000e+000	1.1838e-005	3.3000e+000
6.6425e-006	2.5000e+000	6.3300e-006	2.4000e+000
3.8350e-006	1.6000e+000	3.6625e-006	1.6000e+000
3.8675e-006	1.5000e+000	3.6975e-006	1.5000e+000
6.5025e-006	2.5000e+000	6.1875e-006	2.4000e+000
1.2475e-005	3.0000e+000	1.1938e-005	2.9000e+000
6.5025e-006	2.5000e+000	6.1875e-006	2.4000e+000
3.8675e-006	1.5000e+000	3.6975e-006	1.5000e+000
3.8350e-006	1.6000e+000	3.6625e-006	1.6000e+000
6.6425e-006	2.5000e+000	6.3300e-006	2.4000e+000
1.2398e-005	3.3000e+000	1.1838e-005	3.3000e+000
6.0250e-006	2.4000e+000	5.8250e-006	2.5000e+000
3.1200e-006	1.7000e+000	3.0125e-006	1.7000e+000
2.1823e-006	1.4000e+000	2.1023e-006	1.4000e+000
1.5405e-006	1.7000e+000	1.4820e-006	1.7000e+000

Table A1.10

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6009 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
7.7114e-006	1.9000e+000	7.3657e-006	1.8000e+000
4.7200e-006	1.2000e+000	4.5014e-006	1.2000e+000
4.2357e-006	1.0000e+000	4.0486e-006	1.0000e+000
7.3000e-006	1.7000e+000	7.0129e-006	1.7000e+000
5.8814e-006	1.5000e+000	5.6200e-006	1.5000e+000
3.9014e-006	1.0000e+000	3.7200e-006	1.0000e+000
5.8814e-006	1.5000e+000	5.6200e-006	1.5000e+000
7.3000e-006	1.7000e+000	7.0129e-006	1.7000e+000
4.2357e-006	1.0000e+000	4.0486e-006	1.0000e+000
4.7200e-006	1.2000e+000	4.5014e-006	1.2000e+000
7.7114e-006	1.9000e+000	7.3657e-006	1.8000e+000
4.7200e-006	1.2000e+000	4.5014e-006	1.2000e+000
4.2357e-006	1.0000e+000	4.0486e-006	1.0000e+000
7.3000e-006	1.7000e+000	7.0129e-006	1.7000e+000
5.8814e-006	1.5000e+000	5.6200e-006	1.5000e+000
3.9014e-006	1.0000e+000	3.7200e-006	1.0000e+000
5.8814e-006	1.5000e+000	5.6200e-006	1.5000e+000
7.3000e-006	1.7000e+000	7.0129e-006	1.7000e+000
4.2357e-006	1.0000e+000	4.0486e-006	1.0000e+000
4.7200e-006	1.2000e+000	4.5014e-006	1.2000e+000

Table A1.11

Neutron fluxes n/cm^2s and corresponding relative statistic errors (%) for Monte Carlo calculations for 6010 container pattern:

E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
9.1617e-006	1.7000e+000	8.7700e-006	1.7000e+000
5.1767e-006	1.2000e+000	4.9533e-006	1.2000e+000
4.4767e-006	1.1000e+000	4.2950e-006	1.1000e+000
8.2250e-006	1.7000e+000	7.8633e-006	1.6000e+000
6.3500e-006	1.5000e+000	6.0650e-006	1.5000e+000
3.9833e-006	1.0000e+000	3.8000e-006	1.0000e+000
6.3500e-006	1.5000e+000	6.0650e-006	1.5000e+000
8.2250e-006	1.7000e+000	7.8633e-006	1.6000e+000
4.4767e-006	1.1000e+000	4.2950e-006	1.1000e+000
5.1767e-006	1.2000e+000	4.9533e-006	1.2000e+000
9.1617e-006	1.7000e+000	8.7700e-006	1.7000e+000
5.1767e-006	1.2000e+000	4.9533e-006	1.2000e+000
4.4767e-006	1.1000e+000	4.2950e-006	1.1000e+000
8.2250e-006	1.7000e+000	7.8633e-006	1.6000e+000
6.3500e-006	1.5000e+000	6.0650e-006	1.5000e+000
3.9833e-006	1.0000e+000	3.8000e-006	1.0000e+000
6.3500e-006	1.5000e+000	6.0650e-006	1.5000e+000
8.2250e-006	1.7000e+000	7.8633e-006	1.6000e+000
4.4767e-006	1.1000e+000	4.2950e-006	1.1000e+000
5.1767e-006	1.2000e+000	4.9533e-006	1.2000e+000

Table A1.12
Neutron fluxes n/cm^2s and corresponding relative statistic errors
(%) for Monte Carlo calculations for 6000 container pattern:

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E>0		E> 0.025eV	
P	$\sigma(\%)$	P	$\sigma(\%)$
1.4458e-006	1.7000e+000	1.3768e-006	2.5000e+000
2.1467e-006	1.2000e+000	2.0567e-006	1.4000e+000
3.5217e-006	1.1000e+000	3.3917e-006	1.6000e+000
7.3483e-006	1.7000e+000	7.0383e-006	2.3000e+000
6.7000e-006	1.5000e+000	6.4117e-006	1.8000e+000
4.4267e-006	1.0000e+000	4.2117e-006	1.2000e+000
6.5583e-006	1.5000e+000	6.2433e-006	2.0000e+000
7.8400e-006	1.7000e+000	7.5200e-006	2.3000e+000
4.6533e-006	1.1000e+000	4.4583e-006	1.3000e+000
5.3683e-006	1.2000e+000	5.1433e-006	1.5000e+000
9.3350e-006	1.7000e+000	8.9833e-006	2.2000e+000
5.3683e-006	1.2000e+000	5.1433e-006	1.5000e+000
4.6533e-006	1.1000e+000	4.4583e-006	1.3000e+000
7.8400e-006	1.7000e+000	7.5200e-006	2.3000e+000
6.5583e-006	1.5000e+000	6.2433e-006	2.0000e+000
4.4267e-006	1.0000e+000	4.2117e-006	1.2000e+000
6.7000e-006	1.5000e+000	6.4117e-006	1.8000e+000
7.3483e-006	1.7000e+000	7.0383e-006	2.3000e+000
3.5217e-006	1.1000e+000	3.3917e-006	1.6000e+000
2.1467e-006	1.2000e+000	2.0567e-006	1.4000e+000

Appendix 2.

The equipment and material list Purchased in frame of contract
0002P0004-95 (task order 004)

1. Helium tubes of CM14H type	50	-\$1200
2. PC-486 Notebook class	1	-\$4500
3. Portable printer	1	-\$300
4. Laser printer HP-4L	1	-\$800
5. Computer&printer accessories		-\$500
6. Electronic components		-\$1000
7. Materials (aluminium, steel, textile, etc.)		-\$800
	Total:	-\$9100