UDC 622.83:536

A.N. SHULYUPIN *(Doctor of Engineering Sciences, Institute of Mining, Far East Branch, Russian Academy of Sciences), ans714@mail.ru*
A.V. KONSTANTINOV *(Post-Graduate Student, Institute of Mining, Far East Branch, Russian Academy of Sciences)*
A. A. TERESHKIN *(Post-Graduate Student, Institute of Mining, Far East Branch, Russian Academy of Sciences)*

RISK OF HYDROTHERMAL ERUPTION IN THE COURSE OF DEVELOPMENT OF HIGH-GRADE GEOTHERMAL GROUNDWATER RESERVOIRS*

Under analysis is hydrothermal eruption as a hazardous geological phenomenon occurring in the course of development of high-grade geothermal hot water deposits. The review of the foreign literature reveals numerous events connected with this phenomenon, including catastrophes. In Russian literature, this phenomenon has never been an issue. This article addresses one of the hydrothermal eruption mechanisms associated with the pressure decline in a hydrothermal water reservoir in the course of development. The pressure drawdown leads to formation of steam caps at the top of which the pressure can grow and exceed the lithostatic pressure. This mechanism is accompanied by activation of natural springs. The hydrothermal eruption in Pauzhetskoe field of hot hydrothermal springs (Kamchatka) in 1986–1987 is described in the article. It is highlighted that activation of natural springs and expansion of the area of two-phase inflow in production wells in Pauzhetskoe field in recent years is the evidence of formation of suitable conditions for a hydrothermal eruption with the phase of a steam explosion. A hydrothermal eruption and a rock burst are similar in terms of premonitory symptoms characterizing stress state of surrounding rock mass. This similarity allows recommending the elaborated procedure-and-instrument package of rockburst hazard monitoring and prediction for monitoring and short-term prediction of hydrothermal eruptions. The authors prove it necessary to design and introduce a hydrothermal eruption monitoring and prediction system with a view to enhancing safety of development of high-grade geothermal water resources. Furthermore, it is suggested to turn to research aimed at technologies for prevention of the hazardous geothermal eruption phenomenon, considering specific features of a groundwater reservoir.

Key words: *hydrothermal eruption, steam and hydrothermal springs, development, geothermal reservoir, fluid, bubble-point pressure, steam cap, lithostatic pressure, explosion.*
DOI: *dx.doi.org/10.17580/em.2016.02.12*

Introduction

Utilization of deep heat of the Earth is a dynamical and sustainable trend in the area of development of alternative energy sources [1, 2]. Among the potential and operating fields of geothermal hot water in Russia, of the highest interest seem to be high-grade fields of steam and hydrothermal springs. Russia's first field of steam ad hydrothermal springs — Pauzhetskoe field — was put in operation on the Kamchatka in 1966, which initiated development in the domestic geothermal power engineering. Now both the geothermal power engineering industry and the development of Pauzhetskoe field approach their anniversary with a great deal of unsettled problems [3, 4]. In the midst of them, there are some scientific tasks regarding phenomena seemingly not very significant. For instance, it has recently been noticed that natural heat emissions (steam jets) have activated in the area of producing wells, though such phenomena stopped as development of Pauzhetskoe field commenced. Explanations of this phenomenon suggest that development of a field of steam and hydrothermal springs in a complex structure thermal water reservoir can result in formation of hydrothermal eruption conditions.

The urgency of studying hydrothermal eruptions emerges in connection with the development of the areas prone to such events. Generally, the development of such areas is associated with the exploitation of the high-grade geothermal water fields, simultaneously initiated in a number of countries of the world, including Russia, in the second half of the previous century. The history of the related studies is not long and the subject of the research lacks hardened concepts. For instance, some researchers extend the notion of hydrothermal eruption to geysers [5]. Others assume that the feature of hydrothermal eruptions is there discreteness as against the periodic behavior of geysers [6]. It most frequently happens, e.g. [7, 8], and the present study, that a hydrothermal eruption is understood as a process of uncontrollable liberation of internal energy of geothermal fluid accompanied by rock outburst. In the latter case, a hydrothermal eruption is assumed a hazardous geological phenomenon.

The review of hydrothermal eruption events in [5] includes 5 catastrophes with the total amount of casualties making 192 people. This fact, alone, points at importance of investigation of the discussed phenomenon. The information on hydrothermal eruptions in the territory of Russia is extremely scarce for two reasons. First, the scale of development of domestic high-grade geothermal water resources is twice as lower as it is in the world [1]. Second, the developers of such resources are not interested in placing these phenomena into somebody's attention. Russian literature omits considering this phenomenon. There is one case of an eruption acknowledged by numerous witnesses, including a coauthor of this article, that took place in Pauzhetskoe field of steam and hydrothermal springs in 1986. There are unconfirmed data on eruptions in other areas. For example, the hydrothermal eruption is mentioned in [9] as a probable trigger of the giant landslide that drastically altered the famous Geyser Valley on the Kamchatka in June 2007.

*The study has been supported by the Russian Science Foundation, Project No. 16-17-00018.

An additional stimulus to study hydrothermal eruptions is their connection with mineral mining [8]. The scope of the present study covers a mechanism of hydrothermal eruptions accompanied by activation of natural thermal events, which is assumed a forerunner of a hydrothermal eruption in the area of producing wells in Pauzhetskoe field of steam and hydrothermal springs.

Hydrothermal eruption mechanism

The description of 5 mechanisms of hydrothermal eruption can be found in [10]. However, the suggested distinctions are related not to the mechanism of an eruption but to its formation conditions and triggers. It seems advisable to distinguish between the mechanisms of initiation conditions, triggering and an eruption itself.

Mechanisms of eruptions rest upon the single physical process of transformation of internal energy of geothermal fluid into kinetic energy of the fluid and enclosing rock mixture in the course of expansion of the fluid due to decompression. An eruption may behave as an explosion (short-term eruption) or a long-continued out-throw, or may contain stages of explosion and long-term out-throw. It is worthy of mentioning that the highest potential of released energy per unit volume under decompression is a feature of aboil water [8].

Triggering mechanisms differ in the ways of fluid decompression inducement such as a decline of the lithostatic pressure, breaching of geothermal reservoir roof, a decrease in the atmospheric pressure, or an increase of the pressure in the geothermal reservoir. These mechanisms can be invoked both by man-made activity (soil excavation, vibration impact, etc.) and by natural events (landsliding, seismicity, etc.).

Favorable conditions for a hydrothermal eruption arise when the force of fluid exceeds the ultimate strength and gravity of enclosing rocks. Actually, this is represented by the excess of the superatmospheric pressure at the roof of a geothermal reservoir over the lithostatic pressure. Also, the favorable conditions include the overshoot of dynamic loads from the side of the bursting fluid over the ultimate strength of enclosing rock and attractive force of detached pieces. In terms of initiation factors, the mechanisms in this category are similar to the triggering mechanisms, though, unlike the latter, they never lead to fast decompression of fluid but only create favorable conditions for the decompression development.

Below, one of the mechanisms of formation of hydrothermal eruption conditions due to a decline of the pressure in a geothermal reservoir in the course of development is considered. The roof of the reservoir is not an even surface, especially in fissure–and–vein reservoirs with anisotropic flow characteristics, which includes all operating domestic fields of steam and hydrothermal springs.

Let a hydrothermal reservoir have two heterogeneities in the roof, in the form of a highly permeable dome rising above the datum level of the roof for a height h, and a channel running through the entire thickness of overlying rock mass (**Fig. 1**). In the initially one-phase flow reservoir (water with a temperature above 100 °C), with the static fluid level above the ground surface, an outflow of hot water, probably with steaming, will be present on the ground surface, in the area of the channel. In the first approximation, the water pressure at the dome roof is given by:

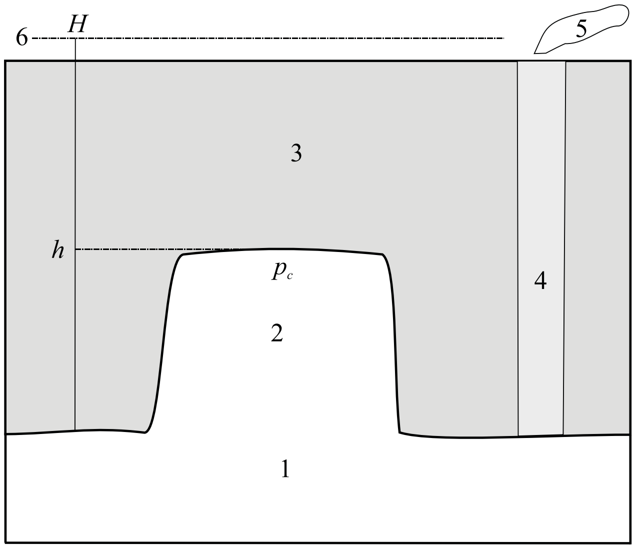

Fig. 1. Schematic profile of geothermal reservoir (initial state): 1 — geothermal reservoir of fluid; 2 — highly permeable dome; 3 — confining formation; 4 — channel; 5 — natural springs; 6 — static water level in the reservoir

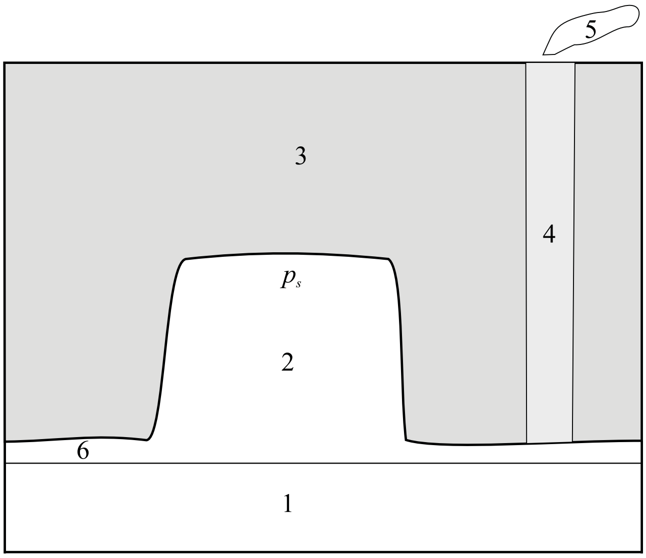

Fig. 2. Schematic profile of geothermal reservoir (current state): 1 — geothermal reservoir of fluid; 2 — highly permeable dome; 3 — confining formation; 4 — channel; 5 — natural springs; 6 — steam cap

$$p_c = p_a + \rho' g(H - h), \quad (1)$$

where p_c is the dome roof pressure, p_a is the atmospheric pressure, ρ' is the density of water, g is the modulus of gravitational acceleration, H is the height of the static water level above the datum level of the reservoir roof, h is the height of the dome roof above the datum level of the reservoir roof.

In case that development activities result in the decline in the reservoir pressure and the static water level is below the ground surface, weakening of natural springs, up to complete exhaustion, should be expected. On the other hand, given that the reservoir pressure drops down to the bubble-point pressure matching with the reservoir water temperature, a steam cap starts shaping in the reservoir (see Fig. 2). In this instance, the natural springs will be likely to activate owing to lesser hydrostatic pressure generated by steam as against water.

The temperature at the dome roof may greatly differ from the temperature in the reservoir owing to heat transfer. Free convection of the fluid in the dome will approach the mentioned temperatures. Under formation of a steam cap, the intensity of the free convection will grow for it is conditioned by both the density difference of the liquid fluid and the density difference of the fluid phases. For this reason, in the case of the steam cap, the dome roof pressure in the first approximation can be accepted equal to the bubble-point pressure conforming with the fluid temperature in the reservoir. Its value may exceed the value existent before the pressure decline in the reservoir under condition that

$$p_s > p_a + \rho' g(H - h)\,, \quad (2)$$

or

$$H - h < \frac{p_s - p_a}{\rho' g}\,, \quad (3)$$

where p_s is the bubble-point pressure conforming with the temperature of the fluid in the reservoir.

Thus, the pressure decline in the reservoir can first be accompanied by the pressure drawdown at the dome roof and, then, by the growth of the latter up to the excess over the initial value. According to [11], of peculiar interest, especially in case of induced hydrothermal eruptions, is the excess of the lithostatic pressure. It is readily found that for the dome roof in **Fig. 2**, this situation is eventual when

$$L < \frac{p_s - p_a}{\rho_r g}\,, \quad (4)$$

where L is the depth of the dome roof, $_r$ is the density of overlying rocks of the dome.

Given that the condition (4) is satisfied, the probability of a hydrothermal eruption considerably grows. It is worth noticing that in the course of the decrease and, then, the increase in the pressure at the dome roof, rock mass may subside and new permeable zones may form. This is a complement factor to add to the formation conditions for a hydrothermal eruption.

Eruption capability of Pauzhetskoe field

Pauzhetskoe field of steam and hydrothermal springs occurs in the southeast of the Kamchatka Peninsula, 30 km eastwards the settlements of Ozernovsky and Zaporozhie situated at the mouth of the Ozernaya River on the fringe of the Sea of Okhotsk. According to [12], this field belongs in the hydrothermal formation adjoining an artesian mountainside and a half-exposed intermount artesian basin with the tectonics-generated drain and leak system and discrete locuses of outflows of the heat-carrying medium the overall heat power of which is estimated as 105 MW. The formation of the discussed field was greatly influenced by tectonic processes and numerous extrusions accompanied with rock crushing and jointing. The geothermal reservoir is composed of Upper Miocene–Pleistocene igneous and igneous–sedimentary rocks; the access to it is gained via hole drilling mostly within the actual elevation interval from –50 to –550 m; the field contains confined groundwater with a temperature up to 228 °C. The structure of the reservoir, the nature of the water host medium and the dense network of faults govern the strata porous–fractured, fractured–porous and fractured–vein patterns of groundwater circulation. The reservoir features pair porosity conditioned by the combination of permeable joints and relatively solid rock blocks. The ratio of the active fracture area in the overall volume of the reservoir is assessed as 0.28. The transmissivity of the reservoir ranges from 190 to 450 m^2/day. The porosity of the enclosing rock mass of the geothermal reservoir is from 0.08 to 0.2. The reservoir is overlaid with relatively impermeable layer of Upper Pliocene–Pleistocene igneous–sedimentary rocks 35–170 m thick. This level has drainage outlets that ensure natural discharge of steam and hydrothermal springs to the ground surface in the form of hot and boiling outflows, steam-and-gas jets and warm ground plots. The basal complex of the reservoir is a thermal-conducting and relatively aquiferous stratum of Oligocene–Miocenen igneous–sedimentary rocks, occurring at a depth below 650 m from the ground surface almost everywhere within the Pauzhetskaya volcano–tectonical depression, and intersected by the most holes drilled to the reservoir. The in-place commercial reserves of the heat-carrying medium (steam and water mix) approved as per Dec 1, 2007 for the estimated lifespan of 25 years make 424.5 kg/s (out of which steam reserves make 35.5 kg/s), including category A — 142.2 (10.2) kg/s; category B — 43.7 (3.5) kg/s; category C_1 — 124.7 (13.4) kg/s; category C_2 — 113.9 (8.4) kg/s.

In 1986 an induced hydrothermal eruption took place in the field during bringing of well 103 into production. The standing water level in the well occurred below the ground surface, and invocation of a well in the steam lift mode needed stimulation. In the case under discussion, stimulation used the method of gas lift treatment. Gas lift was provided by placing carbide fill in the well shaft. It was discovered later on that there was a rupture in the casing at a depth of 5 m. After the stimulation, the well operated in the steam lift mode, and the steam and water mix discharged to the surface both along the shaft and in the hole clearance where to it leaked through the rupture. When the wellhead valve was closed, it never stopped the process, and the steam and water mix jets continued flowing to the surface and throwing pieces of concrete and fragments of rocks to a height of 20 m.

As a result of continuous well operation, a crater with a diameter of round 20 m and 5 m deep appeared on the well site and was filled with water boiling under action of the steam and water mix fed from the well. The water flew from the crater down the side of the hill to one of the tributes of the Pauzhetka River. It took a few years to develop and successfully implement the appropriate engineering solutions on the eruption control. Water was removed from the crater using a channel, which exposed the top portion of the preserved casing string. Assisted with heavy equipment, a purpose-made plug was placed in the well, and a small amount of cold water was injected. Owing to condensation, vacuum was formed in the well; then, the shaft was opened and the well was set into unenergized condition. The exposed casing tube was welded with a flanged socket to install conventional hookup.

At the present day, well 103 is in service and contributes greatly to the overall production of the heat-carrying medium. Moreover, the well has one of the highest work pressure maximum out of all operating wells within the field, which implies its long-term operation prospects. The crater around the well is the only reminder of the experienced eruption.

On evidence of the data [13], the boiling range actively expands in the geothermal reservoir in the area of producing wells in Pauzhetskoe field in the course of development. Considering the structure of the reservoir, this expansion creates conditions for a hydrothermal eruption to take place by the discussed mechanism. The activation of natural outflows (steam jets) in the zone of operating producing wells also points at formation of a steam cap. One more fact to be concerned with is the wellhead pressure growth in the long-out-of-service and suspended (with the closed valve) well K-20 located in close proximity to the activated outflows.

The scenario of the real-time eruption of a steam cap is described in [14]. That event started with the most hazardous stage of a hydrothermal eruption — explosion phase. Probable consequences of such eruption are considerably severer than the aftereffects of the eruption from well 103 in Pauzhetskoe field, though the latter created great problems to an operator. For this reason, the risk of such event in Pauzhetskoe field is worth proper attention and concern.

Placing the bubble-point pressure value to conform with the maximum recorded reservoir temperature (228 °C, 27 bar) and the overlying rock mass density of 2300 kg/m^3 in the formula (4) yields the maximum safe occurrence depth of the steam cap as 115 m. For a reservoir with the average temperature of 190 °C, this value is 50 m.

In order to minimize aggravating aftereffects of a probable eruption, continuous monitoring of processes in the course of the eruption initiation and growth is required. A package of measures to be included in the hydrothermal eruption monitoring with an emphasis laid on the geochemical control methods is proposed in [7]. From the viewpoint of serviceability of a reservoir, it is the most important to carry out the short-term event prediction. In this context, it is worth highlighting the similarity of a hydrothermal eruption and a rock burst in hard mineral mining [15]. The both of the events are the short-term forerunners of an event due to rock pressure. Accordingly, it seems expedient to implement the short-term prediction of hydrothermal eruptions using the methods and systems that are successfully employed in rockburst hazard monitoring [16]. Also, geodetic methods offer useful information.

Furthermore, it is advisable to survey precaution and prevention actions against hydrothermal eruptions in Pauzhetskoe field. There are similar production objects in the world, which possess experience of successful prevention of hydrothermal eruptions by cold water injection in wells in hazardous areas [10, 14]. In the case discussed in this article, it is possible to cool the forming steam cap by injecting liquid phase from producing well separators to suspended well K-20.

Conclusion

The review of the published researches into hydrothermal eruptions yields that this is a hazardous event eventual under development of high-grade thermal water reservoirs. The world's mining practices have realized criticality of this phenomenon. Nonetheless, the current knowledge on hydrothermal eruptions permits no reliance on monitoring and prediction systems available, or on preventive engineering solutions.

In Russia, the hydrothermal eruption phenomenon lacks proper concern though at least one event described in this article has already happened. In the meanwhile, activation of natural thermal outflows in the area of producing wells in Pauzhetskoe field of steam and hydrothermal springs implies initiation of a hydrothermal eruption in conformity with one of the mechanisms studied by the present authors.

The enhancement of safety of high-grade geothermal water reservoirs requires development and introduction of the hydrothermal eruption monitoring and prediction system. It is wise to launch R&D aimed at prevention of this hazardous phenomenon, considering specific features of reservoirs.

References

1. Bertani R. Geothermal power generation in the world 2010–2014 update report. Geothermics. 2016. Vol. 60. pp. 31–43. doi: 10.1016/j.geothermics.2015.11.003
2. Lund J. W., Boyd T. L. Direct utilization of geothermal energy 2015 worldwide review. Geothermics. 2016. Vol. 60. pp. 66–93. doi: 10.1016/j.geothermics.2015.11.004
3. Shulyupin A. N. Problemy razrabotki parogidrotermalnykh mestorozhdeniy Kamchatki (Problems of development of geothermal steam-water fields in Kamchatka). *Gornyi Zhurnal = Mining Journal*. 2015. No. 5. pp. 53–57. doi: 10.17580/gzh.2015.05.11
4. Kolesnikov D. V., Lyubin A. A., Shulyupin A. N. Problemy ekspluatatsii GeoES Kamchatki (Problems of geothermal resources use in Kamchatka). *Elektricheskie stantsii = Power Technology and Engineering*. 2015. No. 4. pp. 16–19. doi : 10.1007/s10749-015-0601-7
5. Rouwet D., Sandri L., Marzocchi W., Gottsmann J., Selva J., Tonini R., Papale P. Recognizing and tracking volcanic hazards related to non-magmatic unrest: a review. Journal of Applied Volcanology. 2014. No. 3:17. pp. 1–17. doi: 10.1186/s13617-014-0017-3
6. Hurwitz S., Lowenstern J. B. Dynamics of the Yellowstone hydrothermal system. Reviews of Geophysics. 2014. Vol. 52, No. 3. pp. 375–411. doi : 10.1002/2014RG000452.
7. Handal S. Hydrothermal eruptions in ElSalvador: a review. Geological Society of America. Special Paper. 2004. Vol. 375. pp. 245–255. doi: 10.1130/0-8137-2375-2.245
8. Brown P. R. L., Lawless J. L. Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere. Earth-Science Reviews. 2001. Vol. 52. pp. 299–331. doi: 10.1016/S0012-8252(00)00030-1
9. Kiryukhin A. V., Rychkova T. V., Dubrovskaya I. K. Formation of the hydrothermal system in Geysers Valley (Kronotsky Nature Reserve, Kamchatka) and triggers of the Giant Landslide. Applied Geochemistry. 2012. Vol. 27. pp. 1753–1766. doi: 10.1016/j.apgeochem.2012.02.011

10. Lawless J. L., Brown P. R. L. Hydrothermal eruptions: mechanisms and implications for prediction. Proceedings 23th New Zealand Geothermal Workshop. 2001. pp. 51–56.
11. Bixley P. F., Browne P. R. L. Hydrothermal eruption potential in geothermal development. Proceedings 10th New Zealand Geothermal Workshop. 1988. pp. 195–198.
12. Asaulova N. P., Vorozheykina L. A., Manukhin Yu. F., Obora N. V. Rezultaty mnogoletney ekspluatatsii Pauzhetskogo geotermalnogo mestorozhdeniya (The results of many years of exploitation of the Pauzjetska geothermal field). *Gornyy vestnik Kamchatki = Mining journal of Kamchatka*. 2009. No. 2(8). pp. 47–56.
13. Shulyupin A. N., Chermoshentseva A. A. Otsenka izmeneniya usloviy v termovodonosnom komplekse Pauzhetskogo mestorozhdeniya parogidroterm (Evaluation of changes in thermal and water-bearing complex of Pauzhetski deposit of steam hydrotherms). *Izvestiya vuzov. Gornyy zhurnal = News of the Higher institutions. Mining Journal*. 2014. No. 4. pp. 82–88.
14. Akasaka C., Takizawa K., Todaka N., Iwasaki O., Tezuka S., Nakanishi S., Shimizu I., Kumazaki N. Restoration from a Large Scale Steam Explosion at the Well Site of the Onikobe Geothermal Power Station. Proceedings World Geothermal Congress. 2015. No. 06032. pp. 1–8.
15. Rasskazov I. Yu. *Kontrol i upravlenie gornym davleniem na rudnikakh Dalnevostochnogo regiona* (Control and management of rock pressure on Far-Eastern region mines). Moscow : Gornaya kniga, 2008. 329 p.
16. *Saksin B. G., Rasskazov I. Yu., Shevchenko B. F. Printsipy kompleksnogo izucheniya sovremennogo napryazhenno-deformirovannogo sostoyaniya verkhnikh urovney zemnoy kory amurskoy litosfernoy plity (Principles of integrated analysis of modern stresses and strains in the outer crust of the amurian plate).* Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh = Journal of Mining Science. *2015. No. 2. pp. 53–65. doi: 10.1134/S1062739115020052*
17. Basmanov O.L., Kiryukhin A.V., Maguskin M.A., Dvigalo V.N., Rutkvist D. Termogidrogeomekhanicheskoe modelirovanie vertikalnykh deformatsiy zemnoy poverkhnosti pri ekspluatatsii Mutnovskogo geotermalnogo mestorozhdeniya (Thermo-hydrogeomechanical modeling of vertical ground deformation during the operation of the Mutnovskii Geothermal Field). *Vulkanologiya i seysmologiya = Journal of Volcanology and Seismology*. 2016. No. 2. pp. 70–82. doi: 10.7868/S0203030616020036